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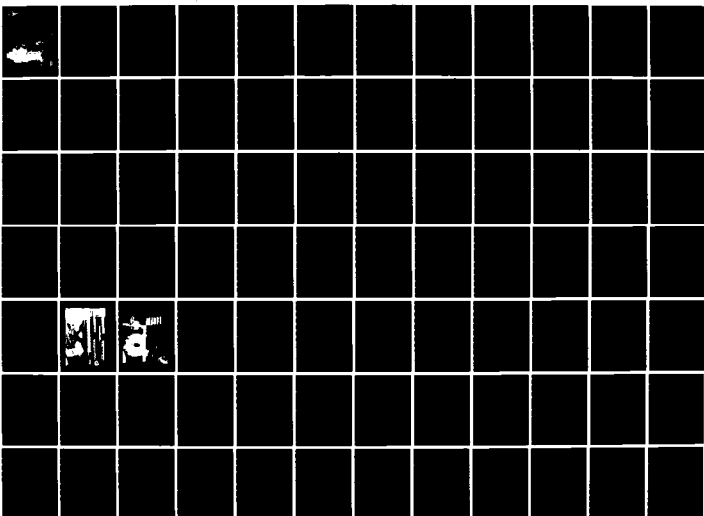
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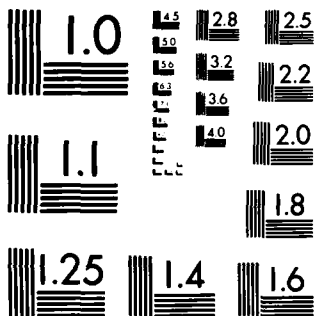
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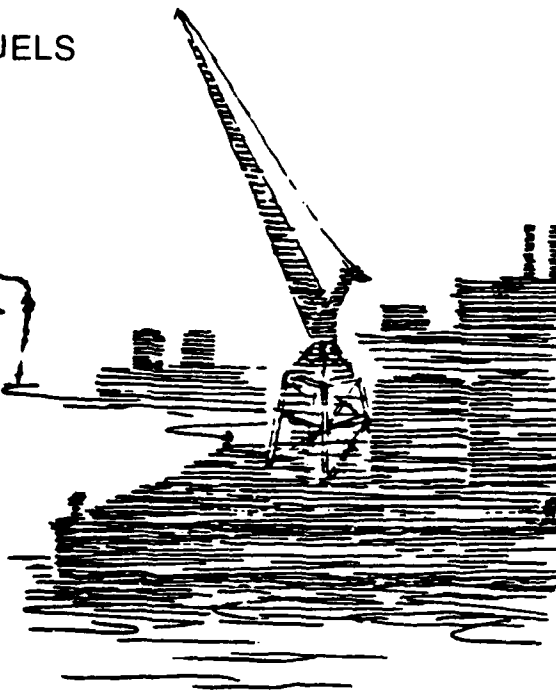
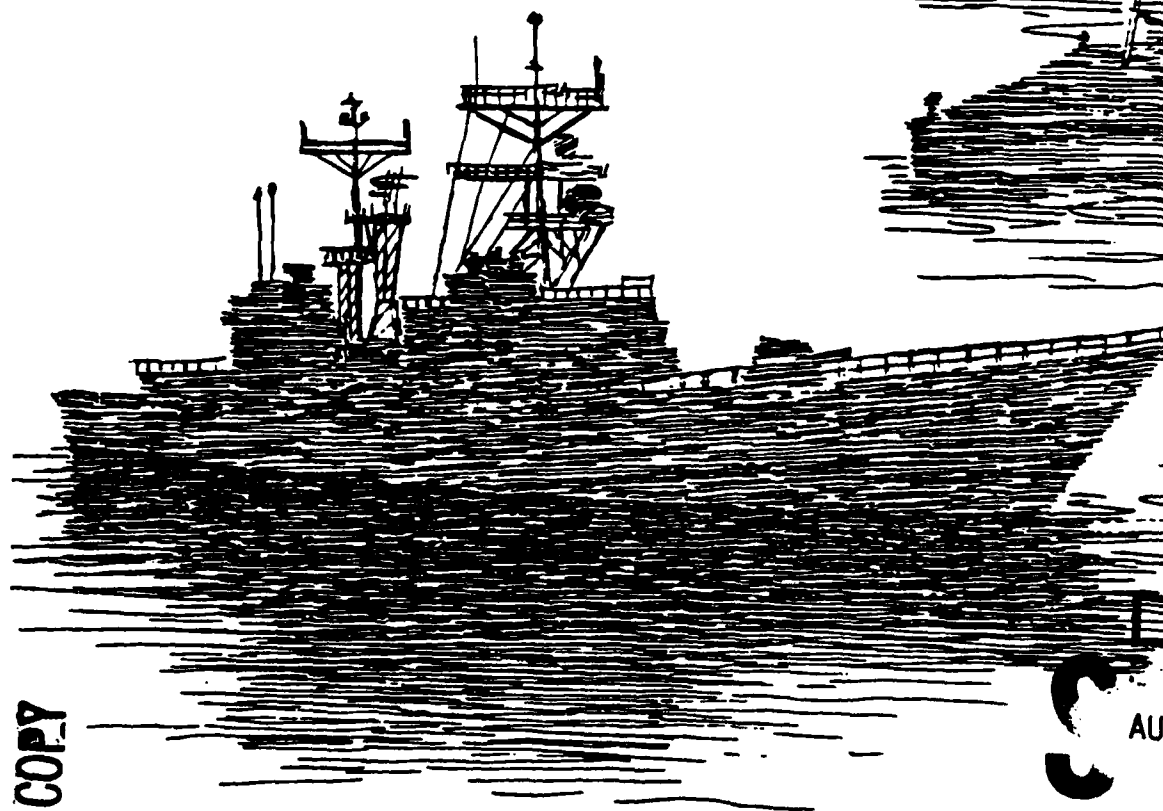


# U.S. NAVY ENERGY R&D



JOINT DOD/DOE SHALE OIL PROJECT  
VOLUME 3 OF 3  
TESTING OF REFINED SHALE OIL FUELS  
FINAL REPORT  
DECEMBER 1983

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JOINT DOD/DOE SHALE OIL PROJECT  
VOLUME 3 of 3  
TESTING OF REFINED SHALE OIL FUELS  
FINAL REPORT  
December, 1983

Prepared for  
U.S. Navy Energy and Natural Resources  
Research and Development Office

by

Battelle Columbus Laboratories  
505 King Avenue  
Columbus, OH 43201

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## FOREWORD

During the period 1976 to 1979 a joint DOD-DOE shale oil project was implemented to provide military specification fuels derived from oil shale. The effort included mining and retorting of oil shale to produce shale crude oil, refining of shale crude oil to produce military specification fuels for test purposes, and the testing of the fuels to determine their suitability for DOD use. The results of this program are presented in three volumes as follows:

- Volume 1. Production of Shale Crude Oil
- Volume 2. Refining Shale Crude Oil
- Volume 3. Testing of Refined Shale Oil Fuels

Volume 3 covers the results of tests using refined shale fuels during the period ending November, 1983. The shale fuels were distributed widely, and research using these fuels was still in progress at that time, although the major evaluation projects had been completed.

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TERMINOLOGY

Throughout this report, shale-derived fuels are identified by the prefix, "shale", and petroleum fuels are identified by their customary designations. Thus, a fuel designated as JP-5, DFM, DF-2, or No.2 fuel oil would be a petroleum fuel. Shale-derived fuels are identified as shale JP-5, shale DFM, shale JP-4, shale JP-8, or shale residual oil.

UNITS

The units of measurement used throughout this report are those used in the reports from which information was taken. Almost all engine test data are reported using English units (foot/pound/degrees F) while much of the analytical data are reported in International units (meter/kilogram/degrees C). Basic conversion factors between these two systems follow:

Conversion Factors

<u>Unit</u>	<u>From</u>	<u>To</u>	<u>Multiply by</u>
Length	ft	m	0.308
Area	ft <sup>2</sup>	m <sup>2</sup>	0.0929
Mass	lb <sub>m</sub>	kg	0.4536
Force	lb <sub>f</sub>	Newtons	4.448
Pressure	psi	kPascals	6.895
Temperature	F deg	C deg	0.55555 C deg = (F deg - 32) x 0.55556
Viscosity	cSt	m <sup>2</sup> s	10 <sup>-6</sup>
Volume	gal	m <sup>3</sup>	0.0037854
SFC (specific fuel consumption)	lb/hp h	kg/J	1.6897 x 10 <sup>-7</sup>

## ABBREVIATIONS

AFB	Air Force Base	l	Liters
AFLRL	Army Fuels and Lubricants Research Laboratory	lb	Pound
AFWAL	Air Force Wright Aeronautical Laboratories	LETC	Laramie Energy Technology Center (DOE)
API	American Petroleum Institute	LERC	Lewis Energy Research Center of NASA
ASME	American Society of Mechanical Engineers		
BaP	Benzo(a)pyrene		
Bbl	Barrel	MARAD	Maritime Administration
BETC	Bartlesville Energy Technology Center of DOE	MDO	Marine diesel oil
BHP	Brake horsepower	MERADCOM	Mobility Equipment Research and Development Command (Army)
BMEP	Brake mean effective pressure	mg	Milligrams
BOCM	Ball-on-cylinder machine	mm	Millimeters
BSEC	Brake-specific energy consumption	MTI	Mechanical Technology Incorporated
BSFC	Brake-specific fuel consumption		
C	Celcius	NAPC	Naval Air Propulsion Center
CA	Crank angle	NASA	National Aeronautics and Space Administration
CAT	Caterpillar	NATO	North Atlantic Treaty Organization
CI	Compression ignition	NAVSSS	Naval Ship System Engineering Station, Philadelphia, PA
CID	Cubic inches displacement	NBS	National Bureau of Standards
CLR	Cooperative Lubrication Research	NO	Nitric oxide
CO	Carbon monoxide	NO <sub>x</sub>	Oxides of nitrogen
CO <sub>2</sub>	Carbon dioxide		
cSt	Centistokes	ONR	Office of Naval Research
		OPEC	Organization of Petroleum-Exporting Countries
		ORNL	Oak Ridge National Laboratory
DDA	Detroit Diesel Allison Division of General Motors Corp	P	Pressure
DF-2	Diesel Fuel, No. 2D, ASTM Spec. D-975	PAH	Polynuclear aromatic hydrocarbons
DFM	Diesel Fuel Marine, specification MIL-F-16884-G	PNA	Polynuclear aromatic
DIF	Differential infrared fluorescence	ppm	Parts per million
DOD	Department of Defense	PROCO	Programmed combustion stratified charge engine
DOE	Department of Energy	psi	Pounds per square inch
DON	Department of the Navy	PWA	Pratt and Whitney Aircraft Company
DOT/TSC	Department of Transportation/Transportation Systems Center		
DTNSRDC	David Taylor Naval Ship Research & Development Center		
EDS	Exxon Donor Solvent, or coal liquid from this process	RR	Railroad
EERC	Energy and Environmental Research Corporation	RPM	Revolutions per minute
EGR	Exhaust gas recirculation	RSO	Residual shale oil
EI	Emissions index		
EP	End point	SAE	Society of Automotive Engineers
EPA	Environmental Protection Agency	SCFM	Standard cubic feet per minute
ERBS	Experimental referee broad-specification fuel (NASA)	SHP	Shaft horsepower
ERDA	Energy Research and Development Administration (now DOE)	Sohio	Standard Oil Company of Ohio
F	Fahrenheit	SRC	Solvent-refined coal
FBN	Fuel-bound nitrogen	STM	Simulated training mission
FIA	Fluorescent Indicator Absorption (ASTM D 1319)	SWRI	Southwest Research Institute
FIMS	Field ionization mass spectrometry		
Ft	Feet	T	Temperature
g	Grams	TACOM	U.S. Army Tank-Automotive Command
GC	Gas chromatograph	TAN	Total acid number
GE	General Electric Company	TBN	Total base number
		TDR	Tube deposit rating (thermal stability test)
HC	Hydrocarbons	USAF	U.S. Air Force
Hg	Mercury	USN	U.S. Navy
HP	Horsepower	USS	United State Ship
hr	Hour		
HX	Heat exchanger	Vis.	Viscosity
IBP	Initial boiling point	W	Mass flow rate
IFT	Interfacial tension	WSD	Wear scar diameter
IGP	Indicated gas horsepower	WSF	Water-soluble fraction
IR	Infrared		
JFTOT	Jet Fuel Thermal Oxidation Tester		
JP-4	Jet Propulsion Fuel, Specification MIL-T-5624-L		
JP-5	Jet Propulsion Fuel, Specification MIL-T-5624-L		
Kcal	Kilocalorie		
Kg	Kilograms		

BACKGROUND

The world and national petroleum crude oil situations indicate a high probability that current military specification fuels will not be available in required quantities and quality in the future. The OPEC oil embargo focused attention on the overall supply and demand for petroleum crude oil on a world-wide basis. It also illustrated the extent to which the United States relies on imported oil and the insecurity of the supply source.

The United States has abundant fossil fuel reserves in the form of oil shale, coal, and tar sands. Research and development has been done on processes for extraction and/or conversion of these energy sources into liquid hydrocarbon fuels comparable to petroleum products. The technology for producing fuels from oil shale is the most advanced, and will probably result in commercialization first. Early small scale testing indicated fuels produced from oil shale are comparable to petroleum fuels and are compatible with military hardware requirements.

During 1974 and 1975, the Navy served as the lead agency in a joint DOD, ERDA, NASA, Coast Guard, and MARAD program to refine 10,000 barrels of shale oil into specification military fuels. Retorting of oil shale to produce crude shale oil was performed by Paraho, the Standard Oil Company of Ohio (Sohio) performed the preprocessing refining studies, and the refining was done at the Gary Western refinery in Fruita, Colorado. The fuels produced included gasoline, JP-4, JP-5/JET-A, DFM/DF2, and Heavy Fuel Oil. The fuels did not meet all of the military specifications; however, hardware tests had favorable results and further analysis and evaluation of refinery processing indicated that specification fuels could be produced if a refinery were configured solely for processing shale oil crude.

The relatively small quantities of fuels produced by the 10,000 barrel project were insufficient for hardware qualification and a decision was made to produce and refine a large quantity of oil shale to support additional qualification tests. This resulted in a contract with the Paraho Development Corporation to produce up to 100,000 barrels of shale oil crude and, under a subcontract with Sohio, to have this crude refined into military specification fuels.

The fuel produced by Sohio at the Toledo refinery met all current military specifications, with minor exceptions. These products were distributed for extensive tests of military and commercial equipment, detailed studies of composition and properties, and evaluation of toxicity. This report summarizes the results of these test and evaluation studies.

The Paraho/Sohio effort was a joint DOD/DOE program, with the Navy serving as the program manager.

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SUMMARY

This report summarizes the results of tests conducted to evaluate fuels produced by Sohio in refining Paraho shale oil, and research on composition and properties of shale fuels. It is the third of three volumes describing the Joint DOD/DOE Shale Oil Project. Volume 1, Production of Shale Crude Oil, describes mining and retorting of shale to produce shale crude oil. Volume 2, Refining of Shale Crude Oil, describes refining of the Paraho crude in Sohio's Toledo refinery, using commercial refining technology and equipment to produce specification products. It also includes analyses of the products produced by Sohio. This report, Volume 3, describes evaluations of the shale fuels produced.

This volume is divided into 17 sections, each describing tests of important Navy equipment or a group of tests carried out by a single agency. Each of the 17 sections is summarized below.

1. Coordination of Shale Oil Fuel Evaluations

Evaluation of refined shale oil fuels was carried out as part of the Joint DOD/DOE Shale Oil Project, managed by the U.S. Navy Energy and Natural Resources Research and Development Office. The objectives of the project were to (1) provide military specification fuels refined from shale oil under a commercial production scenario using commercial refining technology and equipment, in quantities sufficient for evaluation, and (2) evaluate these fuels to determine their suitability for DOD use.

Two shale-derived fuels were evaluated extensively: shale DFM, refined to specification MIL-F-16884G, and shale JP-5, refined to specification MIL-T-5624L. All evaluations of shale DFM were coordinated by the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) at Annapolis; all evaluations of shale JP-5 were coordinated by the Naval Air Propulsion Center (NAPC). Physical and chemical properties of both shale DFM and shale JP-5 were characterized at DTNSRDC and at the Naval Research Laboratory. Toxicology of shale products was evaluated by the Naval Medical Research Institute at Wright-Patterson Air Force Base, Ohio, and by the DOE Oak Ridge National Laboratory at Oak Ridge, Tennessee.

2. Product Distribution and Analysis

The distribution and analyses of shale products are described in detail in Volume 2 of this series and are summarized in this volume for continuity.

Of the 88,225 bbl of crude shale oil received by Sohio, 73,096 bbl were processed to produce 27,672 bbl of finished fuels. These

included 6,165 bbl of JP-5, 462 bbl of JP-8, and 16,375 bbl of DFM. These fuels were distributed widely, with JP-5 distribution controlled by NAPC and DFM distribution controlled by DTNSRDC. In addition, a large number of samples of refinery intermediates, unfinished fuels, and finished fuels was distributed for research on properties and toxicity.

Specification analyses of the shale fuels were carried out by Sohio and by a number of fuel users. In general, the shale DFM met all specifications except that for copper strip corrosion. Minor differences in properties from rail car to rail car were shown in Sohio analyses, and the differences found by various users fell within the same range. The shale JP-5 met all specifications except for copper strip corrosion. Lubricity, which is not controlled by specification, was also poor. At NAPC these deficiencies were corrected by addition of a copper passivator and a corrosion inhibitor.

### 3. NAVSSES Tests of Fuel System Components

NAVSSES performed tests on two typical shipboard fuel oil service pumps and a self-cleaning fuel purifier, and carried out fuel static immersion tests of elastomers and metals exposed to fuel in ship fuel systems. The two fuel pumps evaluated were the screw-type DeLaval CT12LB250 pump, which is the main fuel oil service pump on the CV carriers, and the vane-type Blackmer type X2NAF-NHROV pump, which is the main fuel oil service pump for the FFG-7 class ship. Both pumps passed a 1,000-hour test with insignificant wear, and it was concluded that both pumps were suitable for use with shale DFM.

The Alfa-Laval, Inc., Model USPX Self-Cleaning Purifier was evaluated to determine its effectiveness in removing water, sea water, and AC coarse dust from shale DFM and from a blend of 50 percent shale DFM and petroleum DFM. The purifier was not quite as effective in removing water and dust from the shale DFM and the blend as with petroleum DFM, but appears within the satisfactory range. After 323.8 hours of operation with automatic cleaning every 6 hours the purifier was found to be unaffected by the shale fuels.

Static immersion tests of metallic coupons and elastomeric samples in shale DFM showed insignificant corrosion of metals. Changes in properties of Viton and Buna-N were well within specifications. Lubricity and demulsibility were also found to be within specifications for petroleum DFM. It was concluded that the shale DFM was compatible with current shipboard fuel system materials.

#### 4. NAVSSES Tests of Navy Diesel Engines

NAVSSES carried out extensive tests of three diesel engines typical of those used in the Navy: the Caterpillar 1Y73, a high-speed four-stroke-cycle engine; the Detroit Diesel-Allison 3-71, a medium-speed two-stroke cycle engine, and a Fairbank Morse 8-38ND8-1/8 engine, a 1650 HP opposed piston, two-stroke-cycle engine. Performance and emissions of each engine were measured before and after an endurance test, with shale DFM, and results were essentially the same as for petroleum DFM. The Caterpillar 1Y73 engine was run for 4,000 hr, the DDA-371 engine was run for 5,000 hr, and the Fairbanks-Morse engine was run for 1000 hr. Inspections and wear measurements showed that conditions at the end of the endurance runs were no different than would be expected with petroleum DFM.

#### 5. NAVSSES Tests of Navy Boilers

NAVSSES carried out tests of the principal fleet burners in a single-burner test rig, followed by full-scale tests of three boilers, for the CV-60, the DDG-15, and the FF-1040 ship classes. Performance and emissions for these boilers when burning shale DFM were the same, or only slightly different, from those when burning petroleum DFM. It was concluded that the shale DFM was a satisfactory boiler fuel that could be used with little or no adjustment of burners.

#### 6. Detroit Diesel-Allison Tests of Model 501-K17 Gas Turbine

Performance, emissions, operating characteristics, and endurance of the DDA 501-K17 gas turbine were evaluated in back-to-back combustor rig tests burning shale DFM and a petroleum DFM. No significant differences in performance for the two fuels were found. A 1000-hour endurance test of a 501-K17 gas turbine burning shale DFM was carried out and results compared with previous endurance tests run with petroleum DFM. No significant differences in engine performance before and after the 1000-hr test were found and the engine was in excellent condition after the test. It was concluded that the Model 501-K17 engines in the fleet can operate satisfactorily without penalizing operation, performance, or endurance when using shale DFM of the quality used for this test program.

#### 7. General Electric Tests of GE Model LM-2500 Gas Turbine

Performance, operating characteristics, emissions, and endurance were evaluated in combustor rig tests and full-scale combustor tests of the LM-2500 engine. Shale DFM and a petroleum DFM were burned



in back-to-back tests. The combustor rig tests showed that pattern factor, temperature profiles, light-off characteristics, lean blowout characteristics, and low-power efficiency were the same for both fuels. Engine tests showed that thermodynamic performance, outer combustor liner temperatures and exhaust emissions were the same for both fuels. The only observed difference was in smoke number, which was consistently higher for the shale DFM. However, smoke number was within specifications for both fuels. It was concluded that the shale DFM used for these tests was completely acceptable as an alternative to petroleum DFM.

#### 8. Demonstration Cruise of USS Scott, DDG-995

The USS Scott burned 146,00 gal of shale DFM during a demonstration cruise starting 15 June 1983. The fuel was burned in two GE LM-2500 main propulsion engines and one ship service generator driven by a DDA 501-K17 gas turbine. During six days at sea the USS Scott was operated through all customary operating modes. Total operating time on the LM-2500 engines was 119 hours. Total operating time on the 501-K17 engine, including five days in port, was 166 hours. During this time the other two propulsion engines and one generator were fired with petroleum DFM. Performance with shale DFM was not measurably different from that with the petroleum DFM, and nothing occurred that would indicate that the shale DFM is not a fully satisfactory fuel. However, the test duration was considered too short to be conclusive in defining long-term acceptability.

#### 9. Tests of Navy Aircraft Gas Turbines

The Naval Air Propulsion Center (NAPC) has carried out detailed fuel characterization studies on shale JP-5 followed by a rig test of a TF-30 combustor and full-scale engine tests of T63, T56, TF30, and TF34 engines. Later, shale JP-5 was included among 10 fuels used in combustor rig tests to study the effects of fuel properties on six turbine engines: the T53, T56, T76, T700, F404, and TF30.

Shale JP-5 met all specifications except for copper strip corrosion. Lubricity, which is not controlled by specification, was poor. Corrosion was corrected by addition of 2 ppm of benzotriazole, and lubricity was corrected by addition of 30 ppm of Hitec E-515 corrosion inhibitor. Storage properties were checked over a 2-year period during which buildup of peroxides and sediment was well within specified limits. Thermal stability proved somewhat better than for petroleum JP-5 both before and after storage.

In TF-30-P-412 combustor rig tests conducted by Pratt and Whitney it was found that ignition performance, combustion efficiency and stability, gaseous and smoke emissions, combustor liner temperature,

and combustor exit temperature profile were essentially the same for shale JP-5 as for petroleum JP-5 of the same aromatic content.

An Allison T63-A-5A turboshaft engine was operated on shale JP-5 and other fuels. Exhaust emissions and engine performance for shale JP-5 were the same as for petroleum JP-5. Light-off and time to reach 30,000 rpm was quicker with shale JP-5. After 100 hours of operation on shale JP-5, carbon deposits on the fuel nozzle and igniter were normal.

An Allison T56-A-14 turboshaft engine was tested through a 150-hour Accelerated Endurance Test at sea level conditions at Detroit Diesel Allison Division, Indianapolis, Indiana, using shale JP-5. This test is equivalent to approximately 375 hours of hot-section fleet service life. Performance of the engine and the condition of the hot section after testing were essentially equivalent to experience with petroleum JP-5 fuel. Allison engineers concluded that the shale JP-5 performed satisfactorily.

A General Electric TF34-GE-400 turbofan engine was tested by the General Electric Co. through 25 Simulated Training Mission cycles on petroleum JP-5, followed by 141 cycles on shale JP-5. No detectable differences in steady-state performance were found. Transient testing, consisting of starts, bursts, chops, and bodie stall tests, also confirmed the quality and stability of the shale JP-5. Average cold start and hot restart times were better for the shale JP-5. Inspection of the engine after the tests showed that the engine hot section was in excellent condition. In the opinion of the General Electric engineers the Shale JP-5 performed satisfactorily.

A Pratt and Whitney TF30-P-414 turbofan engine was tested at NAPC for altitude and performance evaluation using shale JP-5 and a high-aromatic petroleum JP-5 fuel. There was no significant difference in engine steady-state performance, ram air altitude restart capability, or afterburner operation for the two fuels. However, afterburner lights were marginally faster for shale JP-5, and smoke number for the shale JP-5 was marginally higher (worse).

The shale JP-5 had somewhat better lightoff and altitude relight characteristics than petroleum JP-5 in most engines. This was found to be the result of a flatter distillation curve for the shale JP-5, with a higher proportion of volatile compounds having low boiling temperatures.

The overall conclusion from all turbine engine tests was that the shale JP-5 evaluated was a fully satisfactory fuel for Navy aircraft turbine engines.

## 10. MERADCOM Fuel Property Investigations and Engine Tests

Evaluations of shale DFM, shale JP-5 and shale JP-8 were carried out for MERADCOM by seven contractors. AFLRL performed specification analyses of the fuels and found that shale DFM and shale JP-8 met all specifications, but the shale JP-5 failed two tests, for smoke point and copper corrosion, by a narrow margin. They also evaluated fuels for storage stability, compatibility with petroleum fuels, hydrocarbon constituents, additive response, and susceptibility to microbiological growth. The three shale fuels proved superior to petroleum JP-5 in storage stability, and compatibility with petroleum fuels was shown. The fuels responded poorly to a corrosion inhibitor, but well to a cetane improver. Microbiological growth was similar to that for petroleum.

Short-term performance tests were carried out on combustors for the Allison T63 and Avco-Lycoming AGT 1500 gas turbines, and on three diesel engines; the DDA 6V-53T, the Teledyne-Continental AVDS-1790-2D, and LDT-465-1C engines. In addition, conversion of fuel nitrogen to  $\text{NO}_x$  was evaluated in a J. I. Case diesel engine. Shale fuels were also tested in an adiabatic engine under development by Cummins. All of these short-term tests showed that shale DFM and shale JP-5 of the quality tested are suitable replacements for petroleum diesel fuel.

Long-term endurance tests of 210 to 400 hours were performed on Allison 3-53, Cummins NTC-400, and Caterpillar 3208NA diesel engines. Performance was measured before and after endurance tests, and engines were disassembled and inspected for wear and deposits after tests. All three engines performed well on shale DFM, and post-test inspections revealed no problems.

An analytical study of the use of shale-derived fuels in U.S. Army generator sets, based on fuel properties, concluded that shale fuels were generally acceptable. However, concern was expressed regarding lubricity and hydrocarbon composition.

## 11. DOE Alternate Fuels Program Engine Tests

The Department of Energy (DOE) has an on-going program to develop technology for use of alternate fuels for highway, railway and marine transportation. As part of this program shale JP-5 and DFM fuels have been used in tests of high-speed and medium-speed diesel engines, gasoline engines, and a Stirling engine. The engines tested included a CLR (Cooperative Lubrication Research) laboratory diesel engine, an EMD 567B, 2-cylinder medium-speed engine, a John Deere 6466-T farm tractor diesel engine, a large Superior 40-X-6 medium-speed diesel engine, and a Wichmann 1AX medium-speed diesel engine and a General Electric Type FDL medium-speed diesel engine. In every case the shale DFM or JP-5 proved to be an acceptable fuel. Performance and emissions when burning shale fuels differed little from those when burning petroleum fuels.

## 12. EPA Tests of Shale-Derived Fuels in Light-Duty Diesel Engines

The Environmental Protection Agency sponsored tests of performance and emission of three types of engines with shale-derived fuels, all in vehicles. Naturally aspirated Volkswagen engines were tested with shale DFM by two organizations, and a turbocharged Volkswagen car was tested with both shale DFM and shale JP-5 by another. An Oldsmobile 350 CID V-8 diesel engine was also evaluated by EPA. The results of all these tests showed that shale DFM and shale JP-5 are satisfactory fuels for automotive diesel engines.

## 13. Miscellaneous Tests

Section 13 summarizes results of five unrelated investigations in which shale DFM, JP-5, weathered gasoline, and heavy distillate fuels were used.

General Motors drove two Oldsmobiles, with 350 CID diesel engines, 30,000 miles each while burning shale DFM. At the end of this period the engines were disassembled and inspected. Performance and emissions were similar to those with DF-2, and no engine distress was found on disassembly. However, starting in cold weather, with temperatures below the freezing point of DFM, was a problem.

Caterpillar Tractor Company evaluated shale DFM in a single-cylinder diesel engine for DTNSRDC. Fuel consumption and emissions at two speeds and loads were similar to those for petroleum DF-2.

Mechanical Technology Incorporated burned shale DFM and four other fuels in a NASA-sponsored automotive Stirling engine project. Tests results for shale DFM and DF-2 fuels were similar.

Westinghouse, under an EPRI contract, burned a heavy shale distillate containing 0.33 percent nitrogen, in rig tests of a gas turbine combustor, to study the effectiveness of water injection and emulsification of water and fuel to suppress conversion of fuel-bound nitrogen to  $\text{NO}_x$ . It was shown that neither water injection nor emulsification was effective in suppressing  $\text{NO}_x$  from fuel-bound nitrogen.

Ford Motor Company burned weathered shale gasoline, an unfinished naphtha cut from the refinery shale oil run, in a single-cylinder PROCO engine. Indolene clear was burned as a reference fuel. The octane number of the shale weathered gasoline was low and the volatility high compared with those of indolene. As a result, the shale fuel was not as satisfactory as the indolene. Shale naphtha would require upgrading of octane number to be a suitable automotive fuel.

#### 14. Shale Residual Fuel Tests

Shale residual fuel was burned in a Brown Boveri heavy-duty industrial type gas turbine, and in an APE Allen medium-speed diesel engine used widely with residual fuels. In the gas turbine test it was found that combustor liner temperatures correlated with fuel hydrogen content, and were comparable to those for a petroleum DF-2 diesel fuel. Emission levels were also acceptable. The APE Allen diesel engine used for these tests was a 6-cylinder engine with 9.5-inch bore, 12-inch stroke, pressure ratio of 12, and power rating of 774 HP at 750 RPM. It utilizes a 4-stroke cycle with turbocharging and aftercooling. Initial performance tests showed that performance with shale residual fuel was identical to that with DF-2 diesel fuel. Inspection of the engine after a 115-hour endurance test showed no engine distress. It appears that the shale residual fuel is a suitable fuel for heavy-duty gas turbines and for heavy-duty diesel engines of the class tested.

#### 15. Chemical Characterization of Shale Fuels

This section reviews research to characterize shale fuels. The subjects covered included thermal and storage stability, characterization of organic compounds, distribution of nitrogen heterocyclic compounds by type in various fractions of shale fuels, hydroperoxide formation in shale fuels, and growth of microbiological organisms in shale fuels.

#### 16. Toxicology of Shale Oil and Shale Products

The toxicology of shale oil and shale products has been investigated in detail through programs of the DOE Oak Ridge National Laboratory and the Naval Medical Research Institute, Toxicology Detachment. In the Oak Ridge program, 11 types of shale derivatives were used by 19 investigators. The Navy program was concerned principally with shale DFM and shale JP-5. The results from these programs show that highly refined shale JP-5 and shale DFM have toxic and mutagenic properties that are nearly identical to those of their petroleum counterparts. However, shale crude and processing intermediates are somewhat more detrimental to health than petroleum materials, but less detrimental than coal-derived materials. The species most responsible for detrimental health effects are polynuclear aromatic compounds, particularly those containing nitrogen or oxygen. These are reduced significantly in hydrotreatment to produce specification fuels.

#### 17. Conclusions

The overall conclusion from the Joint DOD/DOE Shale Oil Project is that shale crude can be processed at commercial scale using conventional petroleum refining equipment and procedures to produce JP-5

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and DFM fuels that meet all military specifications and that perform satisfactorily in diesel engines, gas turbines, and boilers.

## 1. COORDINATION OF SHALE OIL FUEL EVALUATIONS

Evaluation of refined shale oil fuels was carried out as part of the Joint DOD/DOE Shale Oil Project, managed by the U.S. Navy Energy and Natural Resources Research and Development Office. The objectives of the project were to (1) provide military specification fuels derived from shale oil under a commercial production scenario using commercial refining equipment in quantities sufficient for evaluation, and (2) evaluate these fuels to determine their suitability for DOD use.

Two shale-derived fuels were evaluated extensively through small-scale tests, large-scale tests and a shipboard sea trial; these were shale DFM refined to specification MIL-F-16884G, and shale JP-5, refined to specification MIL-T-5624L. Small quantities of other shale products were also evaluated.

All evaluations of shale DFM were coordinated by the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) at Annapolis, Maryland, which was designated as lead laboratory for evaluation of shipboard fuels. The DTNSRDC Energy Research and Development Office, Code 2705, arranged for fuel distribution and evaluation contracts with government and industrial organizations. Table 3-2, Section 3, lists those organizations that received shale DFM for evaluation.

All evaluations of shale JP-5 were coordinated by the Naval Air Propulsion Center (NAPC), which was designated as the lead Navy activity for evaluation of Navy aircraft fuels. The NAPC evaluations included tests of typical aircraft turbine engines and combustor rig tests. NAPC also supplied JP-5 for diesel engine tests, to MERADCOM, DOE, and EPA. Table 3-3, Section 3, lists those organizations that received shale JP-5 for evaluation.

Physical and chemical properties of both DFM and JP-5 were characterized at DTNSRDC and at the Naval Research Laboratory, as well as at various contractors' laboratories.

Toxicology of raw shale oil, unfinished shale fuels, and finished shale fuels was evaluated by the Naval Medical Research Institute, at Wright-Patterson Air Force Base, Ohio, and by the DOE Oak Ridge National Laboratory at Oak Ridge, Tennessee.

## 2. PRODUCT DISTRIBUTION AND ANALYSES

### Product Distribution (Reference 2-1)

Sohio's Toledo refinery received 88,225 barrels of Paraho shale oil in early November, 1978. By December 4, 1978, 73,096 barrels had been processed to products, but subsequent guard bed plugging terminated operations. The remaining 15,129 barrels of shale oil were not refined.

The distribution of additives in products shipped from the refinery was not necessarily uniform, as additives were added batch-wise to each rail tank car before shipment.

The jet fuels and DFM produced were acid-clay treated to reduce nitrogen content, with some fuel loss.

The fuels produced, treated, and shipped were as follows:

	<u>Percent of Crude</u>	<u>Barrels Produced</u>	<u>Barrels Treated &amp; Shipped</u>
Gasoline Stock	10.6	7,718	0
Jet Fuel JP4	0	0	0
JP5	9.3	6,828	6,165
JP8	0.7	490	462
DFM	24.9	18,234	16,375
Residual Fuel	50.9	37,220	4,670
Total Products	<u>96.4</u>	<u>70,490</u>	<u>27,672</u>
Shale Oil Processed		73,096	
Shale Oil Not Processed		15,129	
Shale Oil Received		88,225	

The remaining products of gasoline stock and the bulk of the fuel oil produced, together with the unrefined shale oil, were absorbed by the refinery.

Table 2-1 lists the recipients of shale oil products shipped from the Toledo refinery, with the quantities shipped to each. The shale fuels were subsequently re-shipped to the various organizations that carried out evaluations.



Table 2-2 lists organizations that received DFM, with the quantities shipped to each.

Table 2-3 lists participants in the JP-5 test program. The quantity of JP-5 shipped to each participant is not available.

Throughout the refinery run, samples of shale oil and various finished and unfinished refinery products were collected and distributed to six laboratories. These samples have been used for a number of research studies on fuel composition, distribution of hydrocarbon and non-hydrocarbon constituents, and toxicity of various fuel fractions.

Table 2-4 lists the recipients of shale oil refinery samples, and Table 2-5 lists the types of samples collected and distributed. The samples sent to Dr. Rightmire were used for processing studies and fuel analyses reported in Volume 2 of this series. Those sent to other recipients have been used for research leading to a number of publications. Research using these samples is still in progress.

#### Sohio Analysis of Shale Products

Analyses of DFM and JP-5 for all specified characteristics were carried out by Sohio before they were shipped from the refinery. Each railroad car was sampled using a thief, and the thief samples from 70 rail cars were grouped into four composite samples of JP-5 and five composite samples of DFM.

Table 2-6 lists properties of DFM samples analyzed by Sohio, with requirements specified by MIL F-16884 G. These analyses show that all of the specified requirements for DFM were met with the exception of copper strip corrosion. The values measured ranged from ratings of 1A to 2C, compared with a maximum specified value of 1.

Table 2-7 lists properties of JP-5 samples analyzed by Sohio, with JP-5 requirements as specified by MIL-T-5624 K. The measured values met specifications except for the following exceptions:

1. The copper strip corrosion rating for the four samples all exceeded the specified maximum rating of 1A, with three samples rated at 2C and one at 4A.
2. For one sample the reported aromatic content was high, at 30.5 percent, and the reported olefin content was high, at 6.9 percent. We believe that these values may not be correct, because both the smoke point and the aniline point of this sample were the same as for other samples. Smoke point and aniline point are indicative of aromatic and olefinic content, and should reflect large differences.

Samples of both DFM and JP-5 were sent to other laboratories for analysis, and for detailed study of composition beyond specifications. The analyses reported by these other laboratories were, in general, similar to those reported by Sohio.

Throughout this report, fuel analyses conducted as part of tests of apparatus using shale DFM or shale JP-5 are reported along with other test data. A review of these analyses shows that the values of specified properties reported by users fall within the range of values reported by Sohio.

#### References

- 2-1. Joint DOD/DOE Shale Oil Project, Volume 2 of 3, Refining Shale Crude Oil, U.S. Navy Energy and Natural Resources Research and Development Office, Final Report, July 1982.
- 2-2. Provided by R. Giannini, DTNSRDC, Code 2705.
- 2-3. Karpovich, Peter A., "Acceptability of Oil Shale JP-5 Fuel for Navy Aircraft Use", NAPC Report No. NAPC-PE-52, June 1981.
- 2-4. "Sample Requirement Summary" Navy/Sohio (Toledo Refinery) Shale Oil Refinery Run, November 1978.

TABLE 2-1. INITIAL SHIPMENTS OF SHALE OIL PRODUCTS  
FROM SOHIO TOLEDO REFINERY (2-1)

Product	No. of RR Cars @ 10,000 gal or 238 bbl ea.	Volume Bbl	Recipient
JP-5	26	6,165	Rickenbacker AFB, Lockbourne, OH.
JP-8	1	462	Wright-Patterson AFB, Fairborn, OH.
DFM	35	8,334	Naval Ship Systems Engineering Station (NAVSSSES), Philadelphia, PA.
DFM	13	3,021	General Motors, Detroit Diesel, Allison Plant #5, Indianapolis, IN.
DFM	1	235	Wright-Patterson AFB, Fairborn, OH.
DFM	<u>21</u>	<u>4,785</u>	DFS Point, National Service Corp., 4820 River Road, Cincinnati, OH.
Total DFM	70	16,375	
Heavy Fuel Oil	9	4,345	U.S. Navy, Mechanicsburg Ship Part Control Center, Mechanicsburg, PA.
Heavy Fuel Oil	<u>1</u>	<u>325</u>	EPA, Naval Ship Yard, Long Beach, CA.
Total Fuel Oil	10	4,670	

TABLE 2-2. FINAL DISTRIBUTION OF SHALE DFM TO  
TESTING ORGANIZATIONS (2-2)\*

Organization	Fuel Quantity	
	Gallons	Barrels
Naval Ship Systems Engrg. Station	227,000	5,405
General Electric Comp. (Gas Turbine)	7,000	167
Detroit Diesel Allison, Div of G.M.	216,295	5,150
DTNSRDC/Annapolis	1,440	2.4
Caterpillar Tractor Company	200	4.8
General Motors Research Laboratory	4,830	115
DOE-BETC	100	2.4
Department of Transportation	5	.12
EERC/Superior Products/DOE	9,000	214.3
General Electric Comp. (Diesels)/DOE	9,200	219
University of Trondheim/DOE	550	13.1
Ford Motor Company/DOE	110	2.6
DOE-BETC	110	2.6
Cummins Engine Company/DOE	1,110	26.4
MERADCOM/TACOM	26,978	642.3
AFLRL/SWRI/MERADCOM	3,135	74.6
EPA - Ann Arbor, MI	100	2.4
Southwest Research Institute	100	2.4
Michigan Technological University	100	2.4
EPA - Research Triangle Park, NC	100	2.4
EPA/SWRI	50	1.2
National Bureau of Standards	110	2.6
DOE/NASA-Lewis	1,045	24.9
Sweden United Stirling/DOE	55	1.3
Pratt & Whitney Aircraft	10	.24
DOE/SWRI (Repository)/NASA	4,000	95.2
Wright-Patterson Air Force Base	2,750	65.4
Naval Research Laboratory	150	3.6
MERADCOM	715	17
USS Scott, DDG-995	172,000	4095.2
TOTAL	688,348	16,389.6

\* The point of contact for shale DFM product distribution was DTNSRDC,  
Code 2705, Energy R&D Office, Annapolis, MD 21402.

TABLE 2-3. PARTICIPATING INVESTIGATORS IN THE OIL SHALE JP-5 TEST PROGRAM(2-3)\*

Laboratory	Fuel Test Program
U.S. Army Research and Technology Laboratories, Ft. Eustis, Virginia	800 SHP Advanced Technology Demonstrator Engine Test
U.S. Army Tank-Automotive Command, Warren, Michigan	Advanced Diesel, AGT 1500 Turbine Engine and Fuel Nozzle Tests
U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia	Material Compatibility
David W. Taylor Naval Ship Research and Development Center, Annapolis, Maryland	Material Compatibility, Storage Stability, Chemical Characterization
Naval Research Laboratory, Washington, D.C.	Toxicity Potential, Chemical Characterization
DOE, Bartlesville, Oklahoma	Diesel Engine Performance
NASA Lewis Research Center, Cleveland, Ohio	Chemical Characterization, Low Temperature Flow Properties
Ford Motor Company, Dearborne, Michigan	Diesel Engine Performance
General Motors Research Laboratories, Warren, Michigan	Diesel Engine Performance
Pratt and Whitney Aircraft Group, East Hartford, Connecticut	TF30 Combustor Rig
Detroit Diesel Allison, Indianapolis, Indiana	T56-A-14 150 Hour Accelerated Endurance Test
General Electric Company, Lynn, Massachusetts	TF34-400 Durability Test

\* The point of contact for shale JP-5 distribution was Mr. C. Nowack, Naval Air Propulsion Center, Trenton, NJ.

TABLE 2-4. RECIPIENTS OF SHALE OIL  
REFINERY SAMPLES(2-4)

- 
1. Dr. R. A. Rightmire  
Sohio Broadway Lab  
Cleveland, Ohio  
(216) 575-4141
  2. Dr. L. B. Yeatts, Jr.  
Chemical Repository Project  
Oak Ridge National Laboratory  
Building 4500S, Room F-160  
Oak Ridge, Tennessee 37830  
(615) 574-4863
  3. Dr. Jon S. Fruchter  
Department of Energy  
Pacific Northwest Laboratory  
329 Building  
Richland, Washington 99352  
(509) 376-3937
  4. Mr. Steve Holmes  
University of Wyoming Research Corporation  
(formerly DOE Laramie Energy Technology Center)  
P.O. Box 3395, University Station  
Laramie, Wyoming 82071  
(307) 721-2371
  5. Dr. R. N. Hazlett, Head  
Fuels Section  
Combustion and Fuels Branch  
Chemistry Division, Code 6180  
Naval Research Lab  
Washington, D.C. 20375  
(202) 767-3559
  6. Mr. Buck Nowack  
Navy Air Propulsion Center  
1440 Parkway Avenue  
Trenton, New Jersey 08628  
(609) 896-5848
-

TABLE 2-5. TYPES OF SHALE OIL  
REFINERY SAMPLES (2-4)

- 
- 
1. Crude shale oil
  2. Hydrotreated shale oil, C<sub>5</sub>+
  3. Gasoline feed stock (weathered)
  4. JP-4 before acid/clay treating
  5. JP-5 before acid/clay treating
  6. JP-8 before acid/clay treating
  7. DFM before acid/clay treating
  8. Finished JP-5 product
  9. Finished JP-5 product without oxidation inhibitor
  10. Finished JP-5 product with inhibitor
  11. Finished JP-8 product
  12. Finished DFM product
  13. Finished DFM product without inhibitor
  14. Hydrotreated residuum
  15. Foul water process condensate
  16. Acid sludge
- 
-

TABLE 2-6 SOHIO ANALYSES OF DFM SAMPLES(2-1)

Car Nos. In Composite	Military Specs F-16884-G	79-0030-5 1-17	79-0050-4 17-34	70-0049-4 35-45	79-7298-5 46-64	79-7299-5 65-70
API Gravity	R	38.1	38.1	38.1	38.1	38.1
Flash, P.M., °F	140 Min.	168	174	168	170	175
Pour Pt., °F	20 Max.	-5	-5	-5	-5	-5
Cloud Pt., °F	30 Max.	-6	-2	-2	-5	-5
T.A.N. Mg KOH/gm	0.30 Max.	0.016	0.005	0.002	0.025	0.010
Neutrality	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
B.S.&Q, Vol.2	-	NIL	NIL	NIL	NIL	NIL
Ash, D-482, Wt.2	0.005 Max.	0.002	NIL	NIL	<0.001	<0.001
Cu. Corr. 3 hr @ 212°F	1 Max.	2C	1A	2C	1A	1B
Aniline Pt., °F	R	147.5	150	149	148	150
Demulsibility-Mil Spec	10 Min. Max.	PASS	PASS	PASS	PASS	PASS
Cetane Number	45 Min.	53.6	50.1	50.1	50.1	49.0
Cetane Index	45 Min.	54.2	54.2	55.0	54.0	54.0
Appearance & Color	C & B/5 Max.	C & B/Clear	C & B/<0.5	C & B/<0.5	C & B/0	C & B/0
Vis. @ 100°F, CST	1.8<Vis<4.5	2.71	2.72	2.73	2.75	2.73
Carbon Residue 10% Bcm Wt%	0.20 Max.	0.26 <sup>1</sup>	0.158	0.208 <sup>2</sup>	0.149	0.141 <sup>3</sup>
ASTM 2274 mg/100 cc	2.5 Max.	0.54	0.23	0.17	0.51	0.51

1. After filtration value was 0.076 mg/100 cc with 0.0 mg/l Pickup of residue on 0.8μ Filter Paper.
2. After filtration value was 0.108 mg/100 cc with 0.0 mg/l Pickup of residue on 0.8μ Filter Paper.
3. After filtration value was 0.074 mg/100 cc with 0.0 mg/l Pickup of residue on 0.8μ Filter Paper.



TABLE 2-7 SOHIO ANALYSES OF JP-5 SAMPLES<sup>(2-1)</sup>

Car No. in Composite	Mil. Spec T-5624 K	TR6669/70 1-7	TR6679/80 8-14	79-7001-5 15-21	79-7000-5 22-26
API Gravity	36<API<48	43.8	43.9	43.9	43.9
Flash, P.M., °F	104°F Min.	142	143	144	145
Freeze, °F	-51°F Max.	-63.4	-57.1	-51.7	-53.5
T.A.N. MgKOH/gm	0.015 Max.	0.014	0.002	0.003	0.002
Aromatics, Vol. %	25% Max.	21.2	30.5*	22.2	21.3
Olefins, Vol. %	5% Max.	2.9	6.9**	1.8	2.3
Doctor (Mercaptan S, Wt %)	0.001 Max.	Sweet	Sweet	Sweet	Sweet
Total Sulfur, Wt %	0.40 Max.	<0.002	<0.002	<0.002	<0.002
Explosiveness, %	50 Max.	7% <sup>2</sup>	6% <sup>2</sup>	6% <sup>2</sup>	5% <sup>2</sup>
Aniline Ft., F	-	136.0	136.5	134.5	136.5
BTU/lb (Aniline-Gravity)	18,300 Min.	18,543	18,547	18,537	18,546
Smoke Pt., MM	19 MM	23	23	22	23
Cu. Corr. 2 Hr @ 212°F	1 B Max.	4A	2C	2C	2C
Vis. @ -30°F, CST	8.5 Max.	7.89	7.92	8.39	7.37
Millipore, mg/liter	1.0 Max.	0.7	0.6	0.7	0.2
WSIM*	85 Min.	94.7	94.6	94.6	94.8
Icing Inhibitor, Vol. %	0.10<JJ<0.15	0.185	0.190	0.160	0.155
ASTM GUM mg/100 ml	7 Max.	0.2	0.0	0.0	0.0
JFTOT @ 500°F Visual	<3 Max.	<2	<2	<2	<2
Max. Spun Tube	17 Max.	0.0	5.5	0.0	0.0
ΔP MM Hg	25 Max.	0.0	1.0	0.0	0.0
ETDR	-	0	55	0	0
Distillation	-	D-86	D-86	D-86	D-86
IBP, °F	-	365	344	348	354
°F @ 10 Vol. %	401 Max.	376	379	377	378
°F @ 50 Vol. %	-	395	400	398	401
°F @ 90 Vol. %	-	440	443	444	443
°F @ EP	554 Max.	484	483	480	484
% Residue	1.5 Max.	1.0	1.0	1.0	1.0
% Loss	1.5 Max.	0.0	0.0	0.0	0.0
C, Wt %	-	86.23	86.38	85.30	85.03
H, Wt %	13.5 Min.	13.63	13.65	13.67	13.55
O, Wt %	-	0.63±0.3	0.68±0.3	0.35±0.3	0.30±0.3
N PPM	-	0.26	0.26	0.75	1.05
S PPM	4000 Max.	<20**	<20**	<20**	<20**
Sulfonates, PPM	-	<0.15	<0.15	0.15	1.5.
H <sub>2</sub> O, K.F. PPM	-	272.5	204.5	95.4	1.5.
Bromine No.	-	-	1.64	-	1.50

\*Average of railroad car thief samples in composite.

\*\*Composite of these four samples was 15.4 PPM by Dohrmann.

### 3. NAVSSES TESTS OF FUEL SYSTEM COMPONENTS

#### Summary

As part of the program to evaluate the suitability of shale fuels for shipboard use, NAVSSES has performed life tests of two typical shipboard fuel oil service pumps and of an Alfa-Laval self-cleaning centrifugal purifier and static immersion tests of materials used in fuel systems. The objectives of these tests were (1) to evaluate the compatibility of current shipboard equipment with shale DFM, and (2) to evaluate potential testing methods and their applications in fuel evaluations.

Two fuel pumps were evaluated, the screw-type DeLaval CT12LB250 pump, which is the main fuel oil service pump on the CV (aircraft carrier) class ships, and the vane-type Blackmer type X2NAF-NHROV pump, which is the main fuel oil supply pump on the gas turbine driven FFG-7 class ships. Both pumps passed a 1,000-hour test with insignificant wear. It was concluded that both pumps were suitable for use with shale DFM of the quality used in the test.

The Alfa-Laval Inc. Model USPX-413-SGD-156N Self Cleaning Purifier was evaluated to determine its effectiveness in removing water, sea water, and AC coarse dust from shale DFM and from a blend of 50 percent shale DFM and 50 percent petroleum DFM. A second objective was to determine whether a clean bowl condition could be maintained without frequent disassembly of the purifier.

In tests with salt water injected at 0.1 percent and 0.4 percent of the fuel flow, water content was reduced well below the 40 ppm engine limit. Sodium content was reduced by 80.5 to 93.3 percent for shale DFM, and by 97.0 to 98.3 percent for the blend, but the sodium remaining in both fuels exceeded the gas turbine limit of 0.3 ppm. In separate tests in which 1000 mg/gal of AC coarse dust was mixed with the fuels, 96.9 percent was removed from shale DFM and 95.1 percent was removed from the blend, leaving 4.7 and 9.57 mg/l in the fuels, respectively. After 323.8 hours of operation with automatic cleaning every 6 hours, the purifier was disassembled, cleaned, and inspected. It was found to be unaffected by the shale DFM.

Static immersion tests of metallic coupons and elastomeric samples in shale DFM were carried out to assess the effects of shale DFM on current shipboard fuel system materials. It was found that corrosion of metals was insignificant, and that changes in properties of Viton and Buna-N were well with specifications. Lubricity and demulsibility were also found to be within specifications for DFM. It was concluded that shale DFM was compatible with current shipboard fuel system materials.

Tests of Main Fuel Oil Service Pumps  
(Reference 3-1)

Objectives

The objectives of these tests were (1) to investigate the effects of shale DFM on selected Navy fuel handling equipment, and (2) to determine the reliability and effectiveness of available monitoring and evaluation techniques for their application in evaluating potential alternate fuels.

Approach

The test was conducted using current shipboard fuel oil service (FOS) pumps from steam boiler and gas turbine propelled vessels. The DeLaval CT12LB250 pump is currently the main fuel oil service pump onboard the CV carriers and the Blackmer type X2NAFE - NHROV is the main FOS pump for the FFG-7 class. The test consisted of 1000 hours of operation interrupted after 600 hours for pump disassembly and inspection. The test agenda consisted of a pre-test evaluation of internal pump parts, dynamic testing (600 hours of operation followed by a mid-test evaluation and a final 400 hours of operation) and a final examination and evaluation of internal pump parts.

Table 3-1 shows the agenda for monitoring test parameters.

Table 3-2 shows the test cycles used for fuel pump tests.

Figure 3-1 shows the arrangement of the NAVSSES Fuel Oil Pump Test Facility used for the pump tests.

Figures 3-2 and 3-3 show the wear parts as tested for the DeLaval and Blackmer pumps.

The test cycles of the DeLaval and Blackmer pumps, Table 3-2, reflect steam boiler and gas turbine vessel fuel flows respectively. Summarizing, the Blackmer and DeLaval pumps were operated at 95 F suction temperature and 50 psi and 400 psi discharge pressures, respectively, while the speeds were varied to simulate constant and cyclic operational flow rates. Both pumps were driven by Dynapower Hydrostatic Transmissions using Model 60 variable displacement pumps and fixed displacement motors. Test operations were shut down for an 8-hour period after each 144 hours of running during which the fuel oil was drained and the system recharged with fresh fuel. This was done to minimize any potential effects created by testing in a recirculating situation.

The data and information obtained were combined and evaluated and also compared to data obtained from a previous 1000 hour test of the DeLaval pump using shale DFM, for a total of 2000 hours.

## Discussion of Results

Pump Wear Measurements. Testing was performed with the intent of (1) evaluating the compatibility of shale DFM with existing shipboard equipment and (2) evaluating available monitoring techniques for their application in fuels-suitability determinations. Monitoring techniques were evaluated for their applicability, quality of data and cost. Testing was performed with the operating profiles and parameter monitoring agenda defined by Tables 3-1 and 3-2. Pre-test, post-test and midpoint examinations consisted of weight, dimensional, compositional and metallurgical analysis of pump internal parts. Operational monitoring consisted of vibration, speed, torque, pressure, and flow analyses.

Metallurgical efforts of the monitoring program included both nondestructive and destructive testing. The fuel oil service pump internals underwent a pre-test evaluation, including photography of all components and potential problem areas. Also, acetate replicas were taken of suspected wear areas. These replicas are used to transfer the exact microscopic mating surface of the part to a thin film. With these replicas, the surface conditions of large parts can be examined at high magnifications with resolutions of up to 3000X without damage to the components.

Midpoint and post-test evaluations consisted of macroscopic and microscopic (scanning electron microscope) examinations. Evaluation of the DeLaval pump was confined to the power rotor, idler rotors, rotor housing, thrust plate, idler stop, and the idler bushing. Evaluation of the Blackmer pump was confined to the rotor and shaft, the valves, push rods, casing, and the end plates (discs). All parts were permanently identified to ensure repeatability of data following midpoint and final disassemblies. Figures 3-1 and 3-2 show the test components specified.

The metallurgical wear evaluations revealed no significant fuel-related wear effects due to the test operations. The most severe operational problem found was slight spalling of the Blackmer pump shaft by the lower bearing, caused by slight shaft misalignment.

Pre-test and post-test pump evaluations included weight determinations. Weight changes observed in both the DeLaval and the Blackmer components were negligible.

Dimensional monitoring of the pump internals was performed using a Boice Acral-Cord, Model 66-201 coordinate measuring machine. All measurements obtained from the DeLaval pump revealed dimensional variations of less than 0.001 inch. Variations of this magnitude are insignificant. Blackmer pump data also revealed no significant changes.

Effects of Fuel Recirculation and Fuel Properties. A secondary consideration of the test effort was to evaluate the effects of

fuel recirculation. Concerns regarding the validity of recirculation testing as a simulation of once-through service conditions were investigated. Shale DFM samples obtained from the barge where the bulk fuel was stored and samples of recirculation fuel were analyzed and compared through lubricity testing, viscosity analyses, and spectrographic and ferrographic techniques to evaluate changes in fuel properties resulting from recirculation.

Lubricity testing was performed according to ASTM D-2266 Option A using a four ball wear tester. Three independent test runs were performed with each of the two fuel samples with a 5 kg load at 1200 RPM for 1 hour. Test results showed an average wear scar diameter of 0.70 mm for the recirculated fuel sample and 0.57 mm for the fuel sample obtained from the barge. These results superficially indicate that the recirculated shale DFM had decreased lubricity. However, precision and acceptance criteria of the test method invalidate this apparent difference. Precision criteria, para. 10 of ASTM D2266, define test repeatability criteria (with testing being done in the same lab by the same operator) as being 0.20 mm with a testing load of 40 kg. The observed difference in the measured scar diameters (0.13 mm) is insignificant based strictly on this precision criteria. In that the fuel samples were tested under a load of 5 kg, the precision criteria becomes more relaxed, again rendering the 0.13 mm difference insignificant. Viscosity analyses also showed negligible changes as pre/post-test fuel viscosities were 2.76 and 2.77 cst at 100 F, respectively.

Spectrographic and ferrographic analyses were performed to assess compositional variations of the fuel. Spectrographic analysis identifies the chemical constituents of the fuel and ferrographic analysis attempts to quantify the particulate elements within the fuel.

Spectrographic analyses of shale DFM samples from the barge and from the recirculated fuel showed no significant differences in composition, although slight variation in nitrogen and sulfur content were found. Nitrogen content of both samples was above 10 ppm. Exxon work has shown that wear is independent of fuel nitrogen content at levels above 10 ppm, but increases when nitrogen content is below 10 ppm. Sulfur content of the samples was found to be 0.0025 percent for the barge sample and 0.0015 percent for the recirculated sample, a difference considered inconsequential. Exxon work has shown that sulfur concentrations below 0.1 percent are identified with high wear levels. Ferrographic analyses, to quantify particulate contamination indicated no differences in types or levels of particulate contamination between the two samples.

Flow Calibrations. Pumps were calibrated before and after each of the seven 144-hour test periods using Invalco 1-1/2-inch turbine flow meters. Changes in pump flow capacity during the 1,000 hour tests were negligible. Pump speed, torque, vibration, pressures, and temperatures were monitored continuously throughout the tests.

### Conclusions

Results indicate the compatibility of the shale DFM with the fuel handling equipment tested. No significant changes were observed in any of the monitored parameters. Results indicate no shipboard fuel handling system modifications are required for operations with shale DFM.

Recirculation of shale DFM did not alter the characteristics of the fuel. Pre-test and post-test lubricity, spectrographic and ferrographic analysis of the fuel revealed no significant alterations of the fuel and no observable impacts upon the fuel properties due to recirculation.

Analysis of the test results revealed sophisticated on-line monitoring techniques were generally inappropriate for this particular test application. It appears more prudent to employ on-line techniques which yield gross indications of performance with subsequent more accurate off-line analysis for data interpretation. Testing confirmed broad band vibration levels, hydraulic driver pressure, operational hours and system flows, pressures, and temperatures as valid and adequate definition of test conditions. Off-line analysis techniques including photomicrography, acetate replicas, chemical analyses, metallurgical analyses and weight and dimensional analyses are available for subsequent data analysis and interpretation as required.

Testing experience indicates no single parameter or monitoring technique as sufficient for fuel suitability determinations. Correlation and compatibility of monitoring techniques must be established so that test reliability is maintained. Test data from a particular monitoring technique must be evaluated, analyzed, and confirmed via complementary and supportive data from other techniques to insure reliability of the results.

Acoustic emission techniques proved very subjective and not particularly useful in this test situation where objective data were sought. The expertise required and the limited number of people familiar with the technique also render it quite costly. Because of the extreme sensitivity and subjectivity of the technique, as well as its associated costs, acoustic emission monitoring is not considered appropriate for this type of testing unless it is the technique itself which is to be evaluated.

Test of Alfa-Laval Model USPX  
Self-Cleaning Purifier  
(Reference 3-2)

Objectives

The objective of this test was to determine whether water, sea water, and a standard solid contaminant (AC coarse dust) could be satisfactorily removed from shale DFM and from a blend containing 50 percent shale DFM and 50 percent petroleum DFM, in the Alfa-Laval Model USPX-413-SGO-15CN self-cleaning purifier. A second objective was to determine whether a clean bowl condition could be maintained without frequent disassembly of the purifier.

The Navy requires that gas turbine fuel contain no more than 0.3 ppm sodium, 2.64 mg/l particulates, and 40 ppm free water. It is important that the purifier remove most or all of the removable contaminants although it is not the final purification device in the ship fuel system.

Procedure

The test was performed in two phases. In Phase 1 tests, a blend of 50 percent shale DFM and 50 percent DFM was used. In Phase 2 tests, 100 percent shale DFM was used. In each phase salt water was injected at 0.1 percent and 0.4 percent of the fuel flow and the water and sodium content of the purified fuel determined. In a second test, AC coarse dust was injected into the fuel at a rate of 1 gram per gallon of fuel and the particulate content of the purified fuel determined. At the beginning of Phase 1 the purifier was operated over a range of conditions to determine the optimum operating conditions. Best results were obtained with a flow rate of 100 gpm, back pressure of 35 psi, and a 173 mm gravity disc, and these conditions were used for both Phase 1 and Phase 2 tests.

Tests Results

Table 3-3 summarizes results of sea-water tests with the blend of 50 percent DFM and 50 percent shale DFM. At the optimum operating condition of 100 gpm, sodium content was reduced from 39.64 ppm to 1.17 ppm, and from 115 ppm to 1.9 ppm. These sodium contents exceed the gas turbine fuel specification of 0.3 ppm, but represent sodium reduction of 97.0 and 98.3 percent, respectively. Total water content was reduced from 851 ppm to 60 ppm, and from 6920 ppm to 63.5 ppm. The free water of 0.001 percent, equivalent to 10 ppm, is well below the engine fuel specification of 40 ppm.

Table 3-4 summarizes results of tests to remove sea water from shale DFM. In four test runs, fuel feed rates were 100, 110, and 120 gpm, and sodium content at the purifier inlet ranged from 9.5 ppm to 3.06 ppm. Sodium content at the purifier outlet was reduced to values from 0.663 ppm to 0.595 ppm. Free water was reduced to zero, and total water was reduced to values of 30 to 39.7 ppm. The sodium values were above the gas turbine specified limit of 0.3 ppm, but other values were well within specifications.

Table 3-5 shows results of particulate removal tests using the 50 percent blend of shale DFM and DFM. AC coarse dust was injected at a rate of 1 gram per gallon of fuel, and samples were taken from the purifier inlet and outlet. The purifier was operated at 100 gpm with back pressure of 35 psi and a 173 mm gravity disc. The average sediment remaining in the fuel was 9.57 mg/l, with an average reduction of 95.1 percent.

Table 3-6 shows results of particulate removal tests using pure shale DFM with AC coarse dust injected at a rate of 1 gram per gallon. For the two large sediment concentrations the particulate concentration was reduced by 96.9 percent, leaving 4.7 mg/l of sediment in the fuel. The low values were below the 1 gram/gal injection rate, but showed some particulate removal at low concentrations.

The purifier was operated for a total of 323.8 hours. During this time the purifier's bowl was cleaned automatically every 6 hours. After each phase of the test the purifier was disassembled, inspected, and cleaned to ensure removal of all residue. Examination of the internals showed that shale DFM did not affect the self-cleaning capability of the purifier.

### Conclusions

The purifier removed over 90 percent of the sodium added to both test fuels, although a value of 0.3 ppm was not attained. It has been shown that water washing improves removal of sodium from DFM, but this should not be required during shipboard operation because the fuel sodium content is usually low.

The purifier removed 99.8 to 100 percent of the free water from shale DFM and appears to satisfactorily control free water contamination.

The sediment level in the shale DFM was reduced by an average of 96 percent when sediment level in the influent averaged 185.5 mg/l. With one pass through the purifier the sediment level was not reduced to the Navy's criteria of 2.64 mg/l. However, data indicate that the sediment level could be reduced below 2.64 mg/l by continuous recirculation of fuel through the purifier.



The self-cleaning operation of the purifier was normal with shale DFM and no difficulties requiring purifier disassembly are anticipated in ship service.

#### Recommendations

It is recommended that sampling of fuel at the following points be carried out during shipboard operation with shale DFM:

1. Fuel as received
2. Fuel entering centrifugal purifier
3. Centrifugal purifier discharge
4. Fuel entering filter/separator
5. Filter/separator discharge.

It is also recommended that fuel be recycled through the purifier to the service tank to reduce sediment level.

#### Static Immersion Tests of Fuel System Materials in Shale DFM (Reference 3-3)

#### Objective

Static immersion tests of metallic coupons and elastomeric samples in shale DFM were carried out to assess the effects of shale DFM on corrosion of metals and on swelling and loss of strength of elastomers.

#### Procedures

The materials selected for static testing represent materials found in fuel systems throughout the fleet. In selecting these materials all fuel-wetted surfaces were considered, including pumps, strainers, filters, heat exchangers, burner nozzles, and piping.

Three test coupons of each metallic material were prepared in accordance with ASTM procedure D-130, and each was placed in a separate test tube of fuel maintained at a temperature of 70 F for a period of 32 weeks. At the end of this time the coupons were washed, re-weighed, and inspected.

Elastomeric materials were tested following ASTM method D-471, for a 70-hour period at 70 F. Physical properties of each specimen, measured before and after immersion tests, were weight, dimensions, hardness, and strength.

tests: The following materials were subjected to static immersion

<u>Material</u>	<u>Specification</u>
Ductile Iron	ASTM A536 Grade 60/40
Carbon Steel	ASTM A109 Grade 10/10
4130 Alloy Steel	Commercial Grade
Stainless Steel	304L QQS 763
655 Silicon Bronze	ASTM B 97
353 Leaded Brass	ASTM B121
510 Phosphor Bronze	ASTM B103
Buna -N	Mil-R-6855
Viton	Mil-R-83248
Asbestos Gasket	HH-P-46-Class 1
Packing	Mil-P-17303
Nylatron	Commercial Grade
Carbon	Crane No. 7250
Carbon	Crane No. 7253

Lubricity of the fuel was checked using ASTM procedure D-226, the 4-ball wear tester, with a 5-kg load at 1200 rpm for 1 hour.

Demulsibility was tested according to ASTM procedure D-1401, mixing shale DFM with natural sea water for 5 minutes at 70 F.

### Results

Test results for shale DFM were similar to those usual for DFM. Corrosion of metal specimens was insignificant. The Buna-N and Viton elastomers showed virtually no adverse effects to immersion in shale DFM. The specification Mil R-83248 allows a 20 percent decrease in tensile strength and ultimate elongation, a 10 percent change in volume, and a  $\pm 5$  point change in hardness. The observed values for Buna-N and Viton were within these limits.

Lubricity measurements showed that the wear scar diameter was typical of those for commercial diesel fuels.

Clean separation of shale DFM and natural sea water occurred within the first 5 minutes after the stirring period, and no true emulsion was formed.

### Conclusion

Results of static immersion tests of both elastomers and metallic test materials indicate that shale DFM is compatible with materials commonly found in shipboard fuel oil service systems. The corrosion of metallic materials tested is insignificant, and changes in elastomeric materials are well within specifications. Lubricity is similar to that for commercial diesel fuels, and demulsibility is well within specifications for DFM.

### Reference

- 3-1. "1000/2000 Hour Fuel Oil Pump Test; Forwarding of Final Report", Memo to Commander, David W. Taylor Naval Ship R&D Center from Commanding Officer Naval Ship Systems Engineering Station, October 28, 1982.
- 3-2. "Paraho Shale Oil and/or Paraho Shale Oil/DFM Mix Purification Process Using the USPX-413-SGD-15CN Centrifugal Purifier; Evaluation of", from Commanding Officer, Naval Ship Systems Engineering Station, to Commander, David Taylor naval Ship R&D Center (Code 2705), 17 June 1983.
- 3-3. "Shale Derived Diesel Fuel Static Immersion Test", Final Report, April 15, 1983.

TABLE 3.1 TEST PARAMETER MONITORING AGENDA FOR  
MAIN FUEL OIL SERVICE PUMPS

## A PRE-TEST

1. Photographs of all parts
2. Replicas of areas of concern
3. Measurement of pump parts
4. Precision weighing of pump parts
5. Fuel analysis

## B MID-POINT

1. Photographs of all parts
2. Photographs and replicas of suspect areas
3. Measurement of pump parts
4. Precision weighing of pump parts

## C FINAL

1. Photographs of all parts
2. Hardness Testing
3. Photomicrography
4. Examination of actual wear surfaces and comparisons with initial replicas using the Scanning Electron Microscope (SEM).
5. Measurement of pump parts
6. Precision weighing of pump parts
7. Fuel analysis

## D DURING TEST RUNS

1. Flow rate
2. Pump shaft torsion
3. Pump vibration signals; vertical, axial and transverse
4. Fluid borne high frequency vibration signals
5. Acoustic emission signals
6. Test system pressures
7. Test system temperatures
8. Operational hours

TABLE 3-2. FUEL OIL SERVICE PUMP TEST CYCLES (3-1)

<u>DeLaval Pump</u>		
<u>Hours</u>	<u>Operating Conditions</u>	
0-32	300 RPM	400 psi Disch
32-35	350 RPM	400 psi Disch
35-42	450 RPM	400 psi Disch
42-43	Cycle 1	400 psi Disch
43-50	450 RPM	400 psi Disch
50-72	Cycle 2	400 psi Disch
72-104	300 RPM	400 psi Disch
104-107	350 RPM	400 psi Disch
107-114	450 RPM	400 psi Disch
114-115	Cycle 1	400 psi Disch
115-122	450 RPM	400 psi Disch
122-144	Cycle 2	400 psi Disch

The definition of the operating profile is as follows:

a. Cycle 1 began with the pump at 200 RPM; following 15 minutes of operation at 200 RPM, the speed was increased\* to 600 RPM; following 15 minutes of operation at 600 RPM, the speed was reduced\* to 200 RPM; after 15 minutes, the speed was increased\* to 600 RPM... This profile was maintained for a 1-hour period.

b. Cycle 2 began with the pump at 600 RPM; following 30 minutes of operation at 600 RPM, the speed was increased\* to 1200 RPM; following 30 minutes at 1200 RPM, the speed was reduced\* to 600 RPM; after 30 minutes, the speed was increased\* to 1200 RPM... This profile was maintained for a 22-hour period.

\* All speed increases/reductions were manually performed and took approximately 2 minutes.

<u>Blackmer Pump</u>		
<u>Hours</u>	<u>Operating Conditions</u>	
0-1	900 RPM	50 psi Disch
1-2	1700 RPM	50 psi Disch
2-3	900 RPM	50 psi Disch
3-4	1700 RPM	50 psi Disch

TABLE 3-3. REMOVAL OF SALT WATER FROM 50 PERCENT BLEND OF SHALE DFM AND DFM<sup>(3-2)</sup>  
 Using USPX-413-SGD-15CN centrifugal purifier  
 Fuel temperature, 80°F.

Fuel Feed, GPM	Salt Water Feed (%)	Mean Values						Back Pressure (psig)	DAM Ring (mm)
		Sodium Content (ppm)		Free Water (%)		Total Water (ppm)			
		INLET	OUTLET	INLET	OUTLET	INLET	OUTLET		
120	0.1	15.97	1.74	0.077	0.013	309.3	72.7	25	178
		15.97	3.76	0.191	0.006	1164.3	105.3	30	178
	0.4	35.48	7.85	0.453	0.038	2360	335	30	178
		26.10	8.35	0.436	0.010	1050	188	25	173
100	0.1	39.64	1.17	0.287	0.001	851	60	35	173
	0.4	114.97	1.9	0.45	0.001	6920	63.5		

TABLE 3-4. REMOVAL OF SALT WATER FROM SHALE DFM AT 80°F<sup>(3-2)</sup>

Fuel Feed (GPM)	Salt Water Feed (%)	Mean Values						Back Pressure (psig)	DAM Ring (mm)
		Sodium Content (ppm)		Free Water (%)		Total Water (ppm)			
		INLET	OUTLET	INLET	OUTLET	INLET	OUTLET		
100	0.1	9.489	0.639	0.087	0	760	39.1	30	178
	0.4	3.348	0.648	0.498	0	4880	39.7		
110	0.4	4.198	0.663	0.340	0	-	-	30	178
120	0.4	3.058	0.595	0.353	0	3200	30		

TABLE 3-5. REMOVAL OF AC COARSE DUST FROM 50 PERCENT BLEND OF SHALE DFM AND DFM<sup>(3-2)</sup>

Sediment Content (mg/l)	
INLET	OUTLET
102	14
199	14
91	11
261	6
260	6
262	6
190	10

Fuel Feed: 100 GPM  
 Back Pressure: 35 psig  
 DAM Ring: 173 mm

TABLE 3-6. REMOVAL OF AC COARSE DUST FROM SHALE DFM<sup>(3-2)</sup>

Sediment Content (mg/l)	
INLET	OUTLET
185	1.0
120	8.4
* 29.8	8.0
* 3.1	2.6
* 2.9	2.0

Fuel Feed: 100 GPM  
 Back Pressure: 30 psig  
 DAM Ring: 178 mm

\* These values are below 1 gram per gallon and, therefore, were not used in calculations.

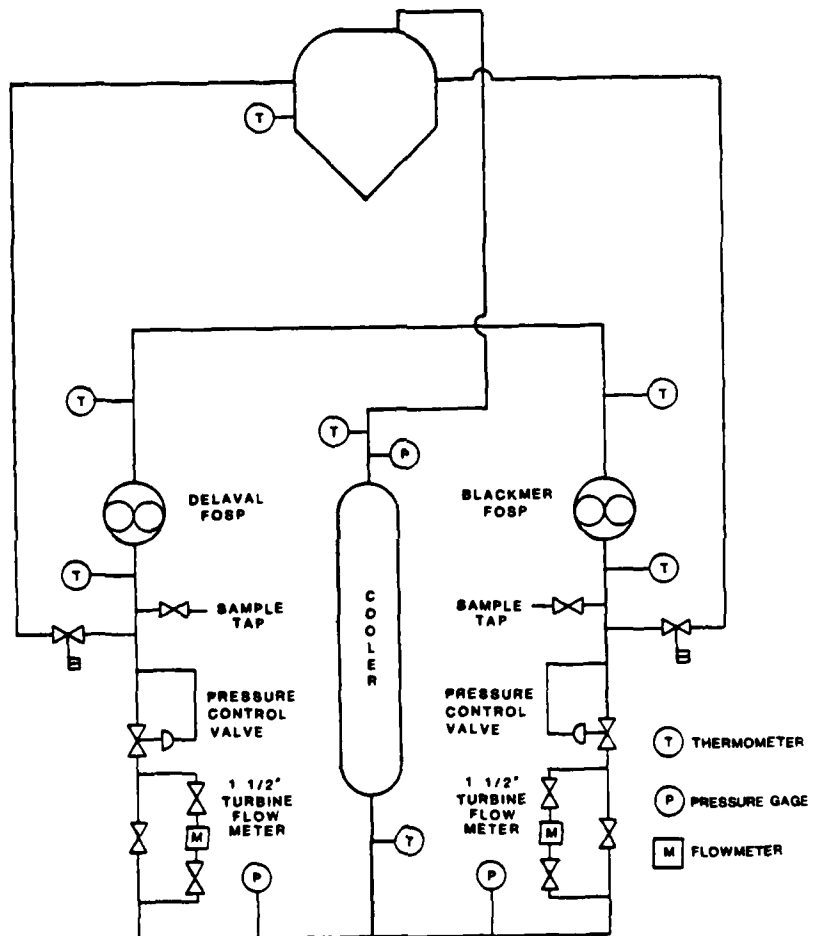


FIGURE 3-1. TEST ARRANGEMENT FOR FUEL OIL SERVICE PUMPS<sup>(3-1)</sup>



FIGURE 3-2. DELAVAL PUMP PARTS (3-1)



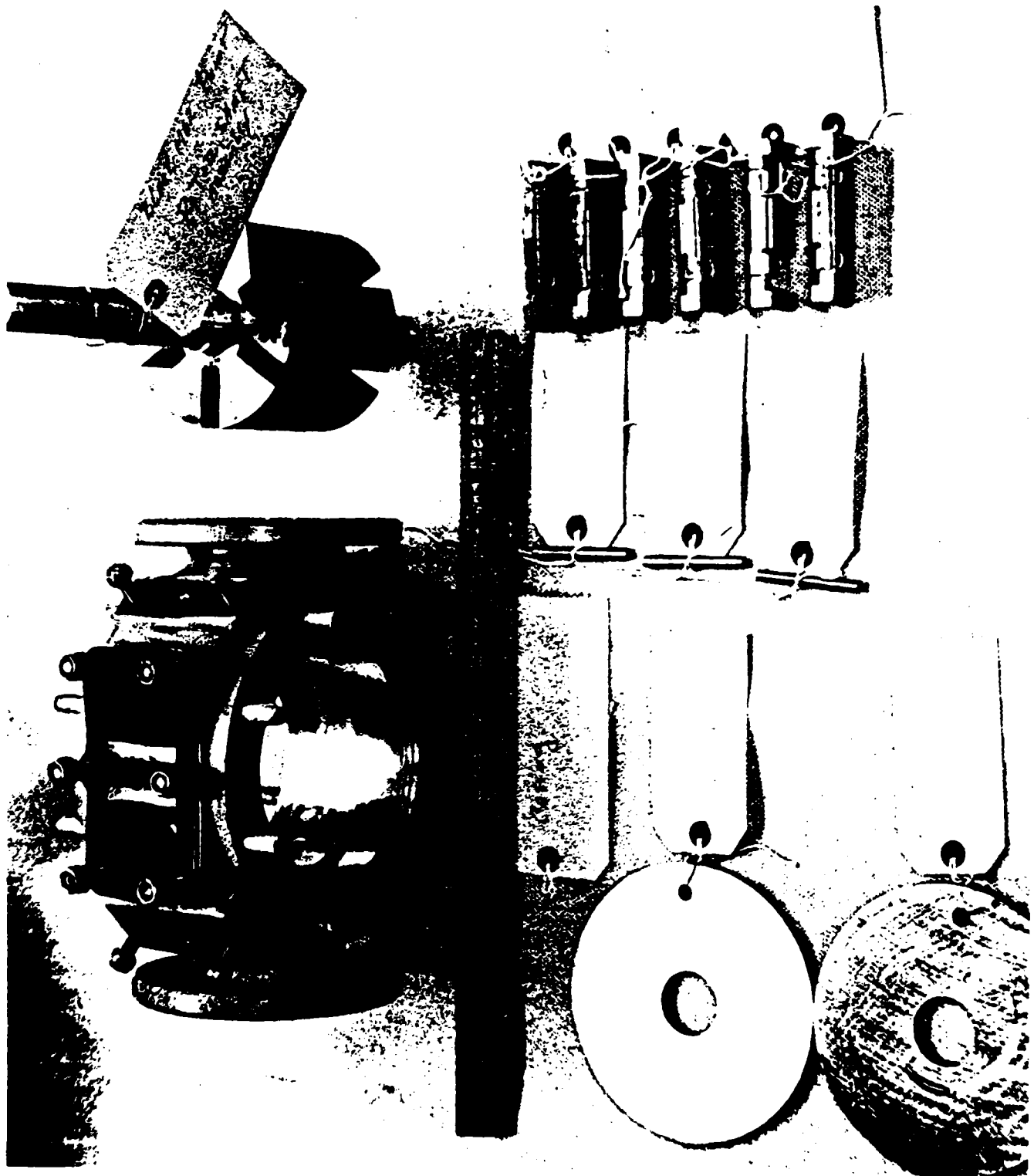


FIGURE 3-3. BLACKMER PUMP PARTS (3-1)

#### 4. NAVSSES NAVY DIESEL ENGINE TESTS (References 4-1, 2, 3)

Three diesel engines typical of Navy engines were tested by NAVSSES (Naval Ship System Engineering Station, Philadelphia) to compare engine performance and durability for DFM with that for shale DFM.

##### Objective

The objective of this project was to determine the suitability of Shale DFM for use in Navy diesel engines. Three engines were tested: the Caterpillar 1Y73, a high-speed four-stroke-cycle engine; the Detroit Diesel 3-71, a medium-speed two-stroke-cycle engine and a Fairbanks Morse 8-38ND8-1/8 engine, an opposed-piston, two-stroke cycle engine. Each test was an extended life test to explore any life-limiting effects of shale DFM.

##### Description of Engines

The Caterpillar 1Y73 engine is a single-cylinder, four-stroke-cycle engine with overhead intake and exhaust valves. The cylinder has a bore of 5.125 in. and a 6.5 in. stroke for displacement of 134 cu in. With 12 psi of charge-air pressure the engine is rated at 43 bhp at 1800 rpm. Although this is a small engine designed to test small quantities of lubricant, the engine has all of the basic components of a modern four-stroke-cycle engine.

The Detroit Diesel Allison (DDA) 3-71 Model 3035C is a 3-cylinder inline, two-stroke-cycle engine with overhead valves. The displacement is 213 cu in, with cylinder bore of 4.25 in. and stroke of 5 in. In order to bring the engine closer to representing the majority of DDA 71 series engines used throughout the Navy, the engine was modified as follows:

1. The two-valve cylinder head assembly was replaced with a four-valve head.
2. The trunk-type piston/connecting rod assembly was replaced by a cross head piston/connecting rod assembly.
3. Higher output, needle valve type N-70 injectors were installed.

With these changes, the engine generated 100 bhp at 2100 rpm.

The Fairbanks Morse Model 8-38ND8-1/8 engine is used as a main propulsion engine in submarines and surface ships, and as a generator

drive in surface ships. The engine is an 8-cylinder, two-stroke-cycle, opposed-piston type with a cylinder bore of 8.125 in. and stroke of 10 in., for displacement of 8,295 cu. in. It is rated at 1500 bhp at 850 rpm. The combustion space is formed between the recessed heads of two pistons that move vertically in opposite directions in each cylinder. The upper and lower pistons drive upper and lower crankshafts that are geared together, with power delivered from the lower crankshaft.

### Description of Engine Tests

#### Engine Preparation and Measurements

Each of the three test engines was run under laboratory conditions, with power absorbed by electric absorption dynamometers. The DDA-371 and the CAT 1Y73 engines were both run through a 32.5-hr test, following which the DDA-371 engine was run for 5,000 hr and the CAT 1Y73 engine was run for 4,000 hr. The Fairbanks-Morse engine was run for 1000 hr.

The DDA 371 engine was completely disassembled before the 32.5-hr test and reassembled with all new wear parts. At the end of the 32.5-hr run the engine was again disassembled, all parts were inspected and measured, and injectors were replaced in preparation for the 5,000-hr endurance test. At the end of the 5,000-hr test the engine was again disassembled and all parts inspected and measured.

The CAT 1Y73 engine was torn down and inspected before the 32.5-hr test and all components were found to be within specified dimensional limits except for intake and exhaust valves, which were replaced. After the 32.5-hr test the engine was disassembled and inspected, and new wear parts were installed in preparation for the endurance test. These parts included a new piston assembly, piston rings, liner, valve inserts, nozzle, main bearings and connecting-rod bearings. The endurance test was terminated after 4,000 hours because of difficulties with the shaft coupling to the dynamometer, instead of after the planned 5,000 hours. The engine was then completely disassembled and inspected, and wear was measured.

The Fairbanks-Morse 8-38ND8-1/8 engine was disassembled before the 1,000-hour endurance test and was found to be in poor condition, with warped connecting-rod bearings, a warped main bearing, severely distorted injector spray patterns, and damaged blower drive coupling. Bearings were restored, crankshaft journals were lapped to original factory finish, pistons were cleaned and new rings installed, and the blower coupling grid was replaced. New spray tips were installed and tested with a Bacharach Nozzle Tester to assure proper injector pressure and spray pattern. All wearing components were measured before and after the 1,000-hour endurance test.

### Fuel-Consumption Tests

Engine fuel consumption measurements were made with DFM and shale DFM prior to the start and after the end of the endurance tests. Weighing scales were used to measure the fuel rates to the DDA and CAT engines, and a turbine meter was used with the Fairbanks-Morse engine. It was found that the Fairbanks-Morse engine could not attain the 110 percent load at all four test speeds at the beginning of the test due to the fact that piston rings were not seated. At the end of the test, 110 percent load could be developed at all speeds, although inspection showed that only the top ring was well seated.

Figures 4-1, 4-2, and 4-3 show specific fuel consumption curves for the three test engines before and after endurance tests. Data for both DFM and shale DFM are shown. These curves show variable differences in specific fuel consumption at different loads, and at different speeds, for the two fuels.

The heat of combustion of the shale DFM was slightly lower than that for the DFM used for comparison, and the specific fuel consumption when burning shale DFM was higher than that for DFM for all three engines. During the 32.5-hr test of the Caterpillar 1Y73 engine a Beta Engine Analyzer was used to evaluate combustion conditions. It was found that the peak pressure with shale DFM occurred earlier and was lower than that for DFM, and flame propagation was more uniform. It is believed that the specific fuel consumption for shale DFM could have been improved by optimization of injector timing and flow rate, but this was not done.

### Emission Tests

Exhaust emissions for each engine were measured during endurance tests, firing DFM and shale DFM for comparison of results.<sup>(4-3)</sup> Emissions were measured at the beginning and end of the 1000-hr tests of the FM-8-38ND8-1/8 engine, and at 2500 hr and the end of the endurance runs of the CAT 1Y73 and DDA 3-71 engines. For each test, data were taken at six load points.

Exhaust gas was sampled using a multi-hole sampler extending across the exhaust pipe of each engine. Conventional analytical instruments were used to measure oxygen, carbon dioxide, carbon monoxide, nitrogen oxides, sulfur dioxide, hydrocarbons, and smoke opacity. Emission values were expressed as grams/brake horsepower hour.

Table 4-2 summarizes diesel engine emission results extracted from Reference 4-3. These data provide a good overview of emissions from the three engines tested. Emissions for the FM-8-38ND8-1/8 engine were similar for shale DFM and DFM at 0 hours. After 1000 hours CO emissions had decreased, NO<sub>x</sub> emission had increased, and HC emission had

increased. The increase in  $\text{SO}_2$  shown is suspect, as the values were near the threshold of sensitivity for the instrument used because of the extremely low sulfur content of the fuels. For the DDA 3-71 engine, smoke opacity at full load increased greatly after 5000 hours, as did CO emission. HC remained low, and  $\text{NO}_x$  was unchanged. For the CAT 1Y73 engine, smoke opacity for shale DFM increased after 4000 hours, but other emissions changed very little.

At the present time there are no EPA standards with which to compare these emission data. Thus, the tests provide baseline data for the engines tested without any basis for comparison with EPA standards.

### Endurance Tests

The endurance tests consisted of a series of 8-hour cycles, with load and speed varied during each cycle as shown in Table 4-1. Lube oil samples were taken after every 100 hours of operation and analyzed spectrographically. Viscosity of crankcase oil was checked every 24 hours, and acidity was checked every 50 hours for the DDA and CAT engines, and every 100 hours for the Fairbanks Morse engine.

The CAT 1Y73 engine encountered one failure during the run. Chips of teflon tape, used to assemble fuel tubing, lodged on the screen of the nozzle spray tip, making engine speed fluctuate erratically. The fuel system was reconnected without teflon tape to eliminate the problem. The endurance run was reduced from the planned 5,000 hours to 4,000 hours because of repeated failures of the drive coupling. This 1-cylinder, 4-cycle engine put severe stress into the flexible circular drive disc, causing it to fail repeatedly.

The endurance test of the DDA 3-71 engine was interrupted after eight hours because of fuel dilution of crankcase oil, caused by leakage of fuel from jumper lines between the fuel manifold and the injector. Lube oil was replaced and fuel lines tightened. After 2112 hours, a lock nut on one of the valve bridges of the No. 1 cylinder loosened, permitting the valve clearance screw to back off. This led to excessive valve clearance, damaging the valve keepers and allowing the exhaust valve and its valve guide to drop down and contact the piston. The severely damaged exhaust valve and its valve guide were replaced and the valve seat insert was reground to assure proper valve seating. No other engine damage was found at that time. At the end of 2504 hours the engine was disassembled and inspected, and was found to be in excellent condition. The engine was reassembled and given a complete tuneup, and the test resumed. At the end of 2584 hours, a hairline crack at the tubing flare of the No. 2 cylinder fuel injector supply jumper was found, and all fuel jumper lines were replaced to avoid reoccurrence of the problem. The remaining 2416 hours of test were completed without difficulty, for a full 5,000 hours of test time.

The Fairbanks Morse engine test was interrupted at 440 hours because of loss of jacket water through a crack in the No. 7 cylinder

water jacket. The crack was stop drilled, opened with a pencil grinder, and filled with Devcon liquid metal, as a replacement water jacket was not available. This patch started to leak at 800 hours of operation and the leakage rate gradually increased until the end of the 1,000-hour test. The only other problem was occasional hard starting of the engine, caused by a malfunction of the governor booster that required manual movement of the fuel rack.

#### Teardown Inspection Following Endurance Tests

Following endurance tests the DDA and Caterpillar engines were completely torn down and wear parts were thoroughly cleaned and measured. The much more complex Fairbanks Morse engine was partially disassembled to obtain representative data. Condition of each engine was about what would be expected following the severe endurance tests, and the same as would have occurred with DFM.

Findings and observations made during the post-endurance tear-down inspection are addressed below.

#### The Caterpillar 1Y73 Engine

1. The thrust surface of the piston was scuffed heavily, especially above the first compression ring.
2. The piston rings, both the compression and oil, were excessively worn, but all piston rings were free to rotate.
3. Combustion deposit buildup on the top of the piston was minimal. Only light carbon buildup in the ring groove and on the side of the piston crown was observed.
4. The top aluminum connecting-rod bearing had warped. Aluminum from the bearing was deposited on the crankshaft journal.
5. Both the valves and valve seat inserts, intake and exhaust, were so heavily worn that a ridge of about 0.125 in. was formed at the edge of the seating surface.
6. The cylinder liner had become out of round and tapered.

#### The DDA 3-71 Engine

1. Measurements indicated all cylinder liner bores had exceeded the specified limits. The No. 2 cylinder liner measurements also indicated a definite out of round condition.

2. Scuffing was observed on the No. 1 and No. 2 cylinder piston skirts and crowns. The top fire ring of both pistons had collapsed.
3. The carbon deposit on the pistons was light.
4. The exhaust valves were exceptionally clean. All valves had shown evidence of blow-by past the seats.
5. Almost no buildup on the injector spray tips could be observed; spray tip holes were clear and unobstructed. Patterns shown on the piston crowns reflected the near ideal spray pattern of the injectors. With the Kent Motor Injector Calibrator, the output of all three injectors was measured to be 83 cc.
6. Main, connecting-rod and piston-pin bearings did not show any signs of abnormality, only normal wear.
7. The press-fitted cam-shaft end bearings were found free to rotate in their housings.

#### The Fairbanks Morse 8-38ND8-18 Engine

Upon completion of the 1000-hour endurance test, the post-endurance tests, fuel consumption and emission, a tear-down inspection of the Fairbanks Morse engine was begun. Due to the enormous amount of work necessary for a complete blueprinting, the engine was only partially torn down. The upper crankshaft was taken out; selected upper and lower piston assemblies were then removed. Selected lower main bearings were removed, inspected, and measured. All injection nozzles were removed and tested. The following is a list of findings and observations made during the partial engine teardown inspection.

1. The upper crankshaft showed little or no wear.
2. With the exception of the No. 9 lower main bearing, the main, con-rod bearings and piston bushings inspected did not show any sign of abnormal wear.
3. The journal and aft thrust surfaces of the No. 9 lower main bearings were warped. The bearing cap was closed in 0.056 in. and the saddle was also pulled in by 0.006 in.
4. Only a light carbon deposit was noticed in the ring grooves and on the side and top of the pistons.
5. With the exception of the top compression rings which were fully seated, the rest of the compression rings were only partially seated.

6. Carbon deposits were barely noticeable on the nozzle spray tips.

All nozzles, tested with the Bacharach Fuel Nozzle Tester, revealed normal spray pattern and proper popping pressure.

#### Discussion of Test Results

The condition of the Caterpillar 1Y73 was observed during the post-endurance teardown inspection. The out-of-round and tapered cylinder liner, scuffed piston, worn piston rings, warped connecting-rod bearing, heavily worn valves and valve seat inserts are considered to be normal and consistent with the extremely long endurance test. The inherent rough engine operating characteristic induced by 720 degrees of crankshaft rotation between power strokes of the single-cylinder four-stroke-cycle engine coupled with the relatively high inertia load of the 500 hp Mid-West dynamometer placed the coupling under tremendous cyclic stress. This cyclic loading subsequently led to the repeated drive coupling failures. The overly worn piston rings, valves and valve-seat inserts accounted for the inability to maintain steady engine speed during attempts to perform the optimization test.

The forced shutdowns caused by the dropping of a No. 1 cylinder exhaust valve and the crankcase lube oil dilution during the DDA 3-71 endurance test were two failures common with the Detroit Diesel 71 Series engine. The excessively worn cylinder liners, scuffed pistons, collapsed fire rings, and blow-by past the valve-seat inserts evident during the teardown would be considered unacceptable under most performance tests. But when one considers the long grueling test of 5000 hours under the Mil Spec Test Cycle, the outcome can only be deemed exceptional.

The problem with the Fairbanks Morse 8-38ND8-1/8 not being able to initially develop the 110 percent power was the result of a combination of the slightly lower heating value of the shale DFM and the calibration of the fuel injection pumps. The fuel injection pumps were set up on DFM to limit the engine output to approximately 1650 bhp. When the engine was operating at 110 percent load with shale DFM, the governor sensed the drop in rpm and attempted to move the rack to increase the fuel. Since the fuel racks were already at the maximum injection position, no extra fuel could be supplied. Due to the lack of proper calibration equipment to assure proper fuel balance between the cylinders, the fuel injection pumps were not calibrated for shale DFM.

The gradual increase in maximum engine power output experienced during the course of the 1000-hour test could be attributed mainly to the slow pace at which the Fairbanks Morse engine compression rings were seated. The phenomenon was quite evident in the post-endurance teardown inspection. The top compression rings were found to be the only ones that were fully seated after 1000 hours of engine operation.



Determining the cause of the lower thrust bearing failure was very puzzling when the failed bearings were examined by themselves. The warped surfaces were the ones which should be only lightly loaded. But when the wear patterns on the vertical drive and the crankshaft gears also indicated the crankshaft was thrust aft instead of forward, the Ajen coupling between the engine and dynamometer was suspected as the possible cause. Consultation with the coupling group in NAVSSES confirmed the suspicion that the Ajen coupling could lock up during operation, preventing free axial movement of the drive shaft. As a result, the thrust bearing would be overloaded due to thermal growth of the shaft.

The engine failures experienced during the course of the endurance test, and the conditions observed during the post-endurance teardown inspections of the Caterpillar, Detroit Diesel, and the Fairbanks Morse engines could not be in any way tied to the shale DFM that was used. They were all caused by support equipment malfunctions or considered as part of the normal course for such a long and demanding test.

The lower exhaust temperature and generally higher brake specific fuel consumption observed both during the 32.5-hour tests and the endurance tests perhaps could be best explained by photographs taken with the Beta Engine Analyzer during the Caterpillar 1Y73 32.5-hour test. The photographs clearly indicated the shale DFM exhibited a slightly lower pressure peak and a more uniform flame propagation when compared to DFM. The shale DFM peak pressure also occurred a few degrees earlier. A lower and earlier peak pressure meant less energy was released during combustion and a higher brake specific fuel consumption was required to develop the same power as was developed with DFM.

The result of the test itself is the best testimony for the suitability of the shale DFM for diesel engine operation. The shale fuel did not contribute to any of the engine failures. Conditions of the valves, pistons, injectors, and nozzles could only be labeled exceptional. Combustion deposit buildup on the valves and pistons was minimal. The Detroit Diesel 3-71 injectors survived the 5000-hour endurance test without a single failure. The injector output only increased by approximately 10 percent. The injection pumps of the Fairbanks Morse engine worked flawlessly throughout the entire test. The fuel nozzles exhibited good spray pattern and proper injection pressure during the post-endurance test. Not once was the crankcase lube oil replaced because of unacceptable test results for acidity or viscosity. The slightly higher brake specific fuel consumption is considered a profitable trade-off for the lower exhaust temperature. The profit would be realized in terms of longer engine life, and fewer piston, valve, and injection equipment failures, especially for the high output/performance engines.

The shale DFM in its present form is highly suitable for shipboard diesel engine applications, and if the brake specific fuel

consumption can be brought to at least equal that of DFM by retarding the injection timing of the engine, the shale DFM will become that much more attractive.

#### NAVSES Recommendations

Optimization of the shale DFM with the Caterpillar 1Y73 engine should be carried out to explore the possibility of reducing the brake specific fuel consumption by retarding the injection timing.

Additional testing should be conducted to further investigate the combustion characteristics of the shale DFM. An engine with the capability of providing firing pressure measurements must be chosen so the Beta Engine Analyzer can be utilized extensively.

Since the long-term tests clearly show that the shale DFM will not cause accelerated wear in any engine wearing components or fuel injection equipment, future testing should concentrate on tests of 500 hours or less.

#### References

- 4-1. Jung, Philip K., "Shale Oil 100,000 BBL Experiment, Diesel Engine Final Report", NAVSES Project T-2551/T-3204, November 1982.
- 4-2. "Diesel Engine Shale Oil Tests, 32.5-Hour Test Results", Memo from Commanding Officer, NAVSES to DTNSRDC, February 26, 1981.
- 4-3. "Evaluation of Emission Products from the Combustion of Diesel Fuel Marine Vs. Shale Diesel Fuel in Steam Generators and Diesel Engines", Final Report, NAVSES Project OM-0539, 30 September 1982.

TABLE 4-1. DIESEL ENGINE ENDURANCE TEST CYCLES (4-2)

## CATERPILLAR 1Y73 ENDURANCE TEST CYCLE

POINT	TIME	ENGINE SPEED RPM	SUPERCHARGE PRESSURE PSI	ENGINE HORSEPOWER BHP
1	2 hr	1800	12	42
2	1 hr	1800	12	35.7
3	10 min	900	0	0
4	1 hr 50 min	1800	12	42
5	10 min	900	0	0
6	30 min	1350	7	21
7	10 min	900	0	0
8	10 min	1800	12	35.7
9	1 hr 50 min	1800	12	42
10	10 min	Shut Down		

## DETROIT DIESEL 3-71 ENDURANCE TEST CYCLE

POINT	TIME	ENGINE SPEED RPM	ENGINE HORSEPOWER BHP
1	2 hr	2100	100
2	1 hr	2100	85
3	10 min	550	0
4	1 hr 50 min	2100	100
5	10 min	550	0
6	30 min	1575	50
7	10 min	550	0
8	10 min	2100	85
9	1 hr 50 min	2100	110
10	10 min	Shut Down	

## FAIRBANKS MORSE 8-38ND8-1/8 ENDURANCE TEST CYCLE

POINT	TIME	ENGINE SPEED RPM	ENGINE HORSEPOWER BHP
1	2 hr	850	1500
2	1 hr	850	1275
3	10 min	300	0
4	1 hr 50 min	850	1500
5	10 min	300	0
6	30 min	640	750
7	10 min	300	0
8	10 min	850	1275
9	1 hr 50 min	850	1650
10	10 min	Shut Down	

TABLE 4-2. SUMMARY OF NAVSSES DIESEL ENGINE EMISSION DATA<sup>(4-3)</sup>

	Smoke opacity, percent(1)	Emissions, g/BHP hr(2)			
		CO	NO <sub>x</sub>	HC	SO <sub>2</sub>
<u>FM8- 38ND8-1/8 Engine</u>					
Shale DFM, 0 hours	11	9.92	12.51	1.31	0.79
DFM, 0 hours	12	10.73	12.58	1.44	0.90
Shale DFM, 1000 hours	34	2.91	17.03	2.44	1.80
DFM, 1000 hours	17	2.68	14.19	2.40	1.03
<u>DDA 3-71 Engine</u>					
Shale DFM, 2500 hours	2	3.28	12.80	0.03	0.20
Shale DFM, 5000 hours	35	16.94	11.94	0.76	0
DFM, 5000 hours	35	16.88	9.08	0.58	0
<u>CAT 1Y73 Engine</u>					
Shale DFM, 2500 hours	21	3.93	3.56	0.13	0
Shale DFM, 4000 hours	12	3.42	3.56	0.57	0
DFM, 4000 hours	37	4.59	3.67	0.52	1.24

(1) at 100 percent load

(2) Weighted mean: value at 50 percent torque x 0.2  
value at 75 percent torque x 0.4  
value at 100 percent torque x 0.4

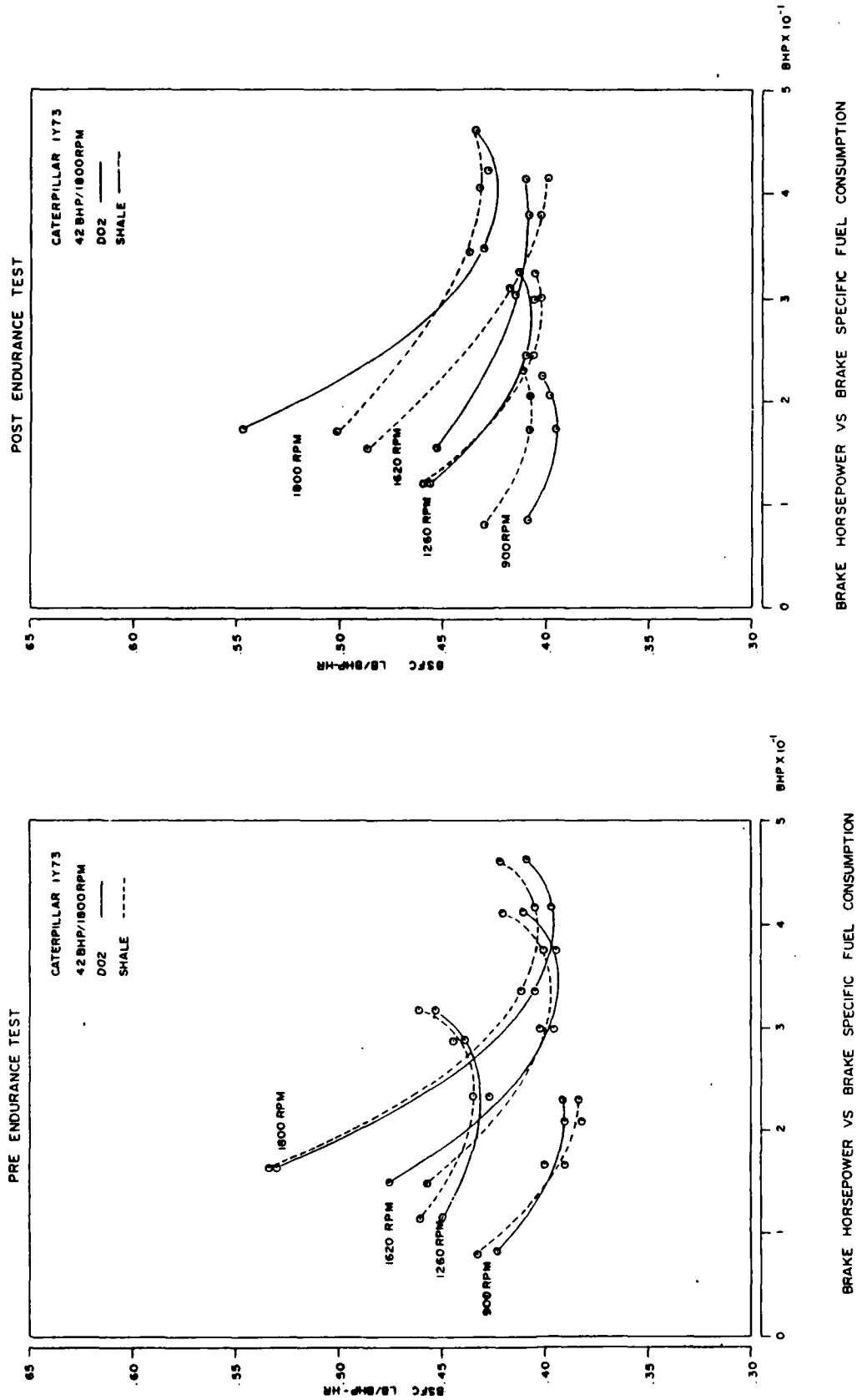


FIGURE 4-1. SPECIFIC FUEL CONSUMPTION CURVES FOR CATERPILLAR 1Y73 ENGINE BEFORE AND AFTER 4,000-HR ENDURANCE TEST. DATA FOR SHALE DFM AND PETROLEUM DFM. (4-2)

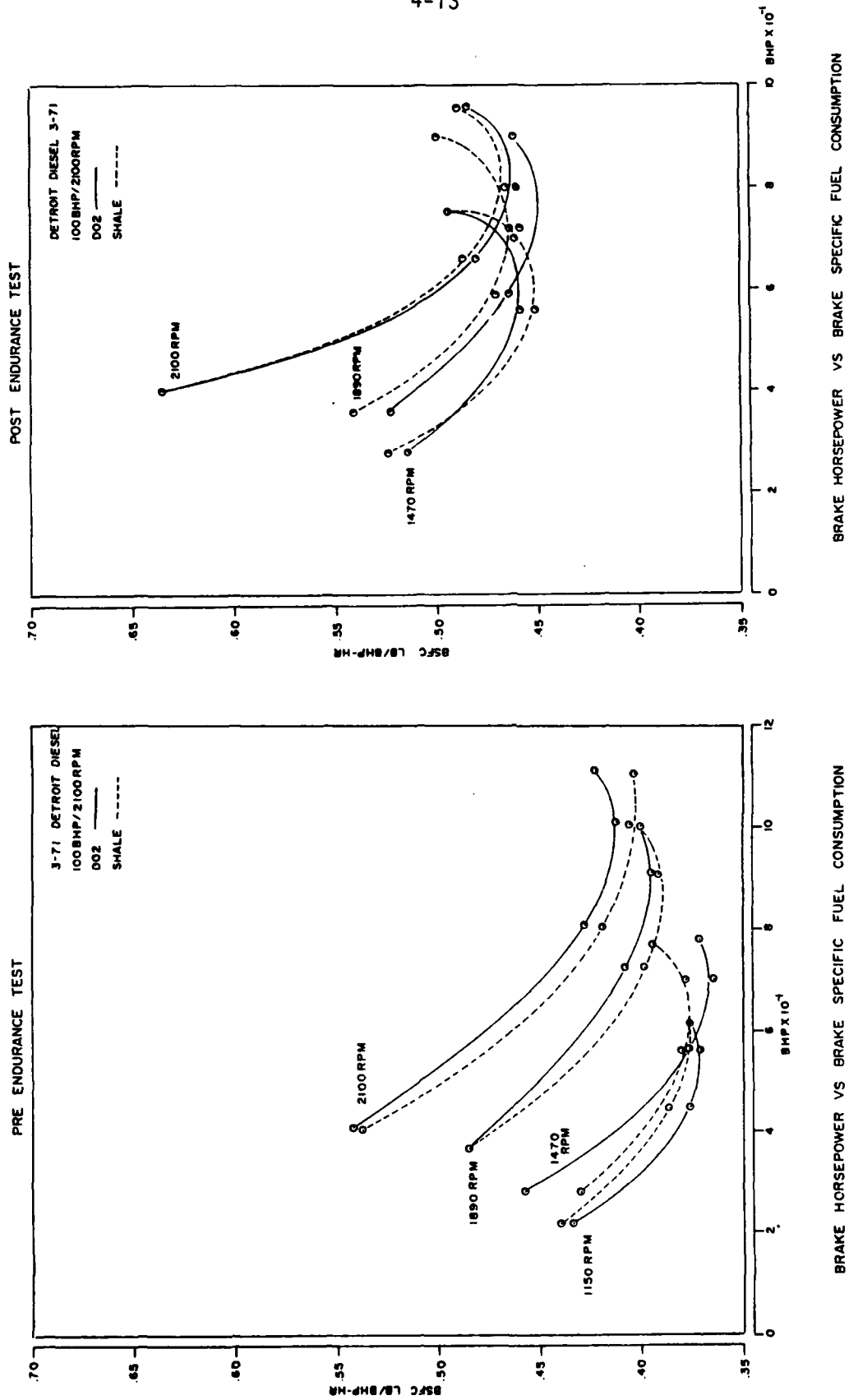


FIGURE 4-2. SPECIFIC FUEL CONSUMPTION CURVES FOR DETROIT DIESEL 3-71 ENGINE BEFORE AND AFTER 5,000-HR ENDURANCE TEST. DATA FOR SHALE DFM AND PETROLEUM DFM. (4-2)

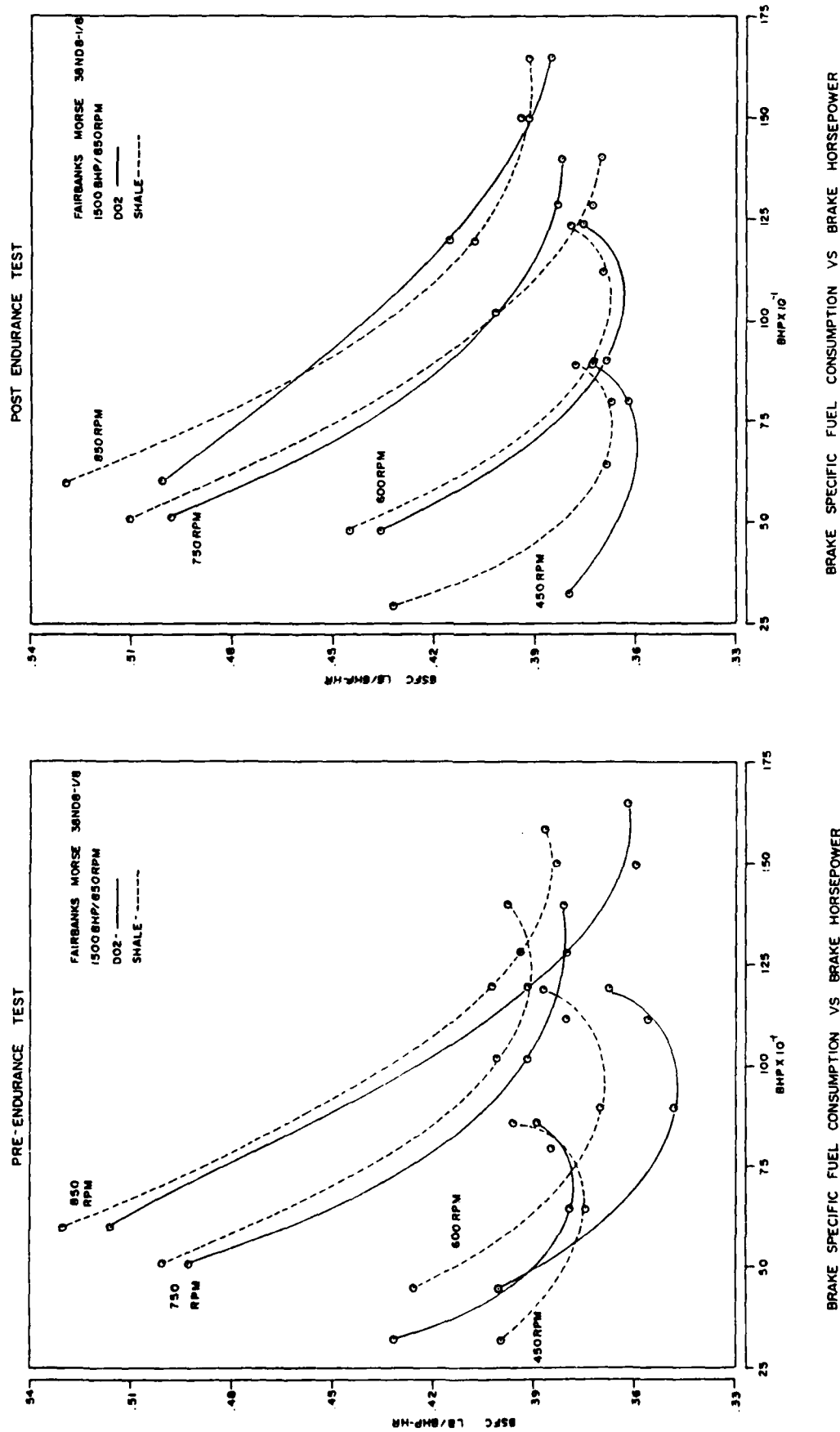


FIGURE 4-3. SPECIFIC FUEL CONSUMPTION CURVES FOR FAIRBANKS MORSE 8-38ND8-1/8 ENGINE, BEFORE AND AFTER 1,000-HR ENDURANCE TEST. DATA FOR SHALE DFM AND PETROLEUM DFM.(4-2)

## 5. NAVSSES TESTS OF NAVY BOILERS

### Summary

NAVSSES (The Naval Ship Systems Engineering Station) at Philadelphia carried out tests related to Navy boilers, including tests in the NAVSSES single-burner test facility and tests of three full-scale Navy boilers. Both performance and emission tests were performed. The basis for all tests was back-to-back testing to compare results for shale DFM to results for petroleum DFM.

Three burner registers were used in the single-burner Combustion Test Facility: (1) a Todd LVC-4M register with a NAVJET steam atomizer and with a VP atomizer, (2) a B&W Iowa-type register with a Racer steam atomizer and with a VP atomizer, and (3) a CE-Wallsend register with CE-Wallsend steam atomizer. The overall results of single-burner tests showed that differences between shale DFM and DFM were quite small, and that no problems should be expected in firing shale DFM to full-scale boilers.

The three full-scale boilers tested were (1) the CV-60 Class boiler, (2) the DDG-15 Class boiler, and (3) the FF-1040 Class pressure fired boiler. Based on the results of boiler tests, it was concluded that shale DFM of the type and quality used for the tests could be used in USN main propulsion boilers with no adverse effects on performance. However, because of slight differences in fuel atomizer calibrations, it may be necessary to change steam atomizer sprayer plates in some boilers and this, in turn, would require recalibration of automatic combustion controls.

It was found that the excess air at which a clear stack was obtained, as excess air was reduced, was slightly lower for shale DFM than for petroleum DFM at lower loads. However, a new, sensitive, continuously recording CO meter showed that operating at this condition produced more CO and, thus, lower efficiency, than with slightly more excess air. It was concluded that the "clear stack" method of optimizing excess air did not produce maximum efficiency and should be revised to utilize a recording CO meter for very significant fuel savings.

Emission measurements showed that boiler emissions met EPA new source standards for both fuels. Direct comparison of fuel effects was difficult, however, because of the sensitivity of emissions to minor differences in excess air.

### Single-Burner Tests (Reference 5-1)

Single-burner tests were conducted in the Combustion Test Facility at the NAVSSES at Philadelphia. This facility consists of a



water-cooled combustion tunnel of 25-square-foot cross section into which a single burner is fired. Equipment used in the fuel system consists of standard Navy components. Specific burner/register combinations used for these tests were (1) the Todd LVC-4M register with a NAVJET steam atomizer and with a VP (Vented Plunger) variable-area mechanical atomizer, (2) the Babcock and Wilcox Iowa-type register with the Racer steam atomizer and with the VP mechanical atomizer, and (3) the Combustion Engineering CE-Wallsend register with a CE-Wallsend steam atomizer. These combinations encompass all burner-register combinations used in the combatant fleet except those in FF-1040-class pressure fired boilers.

The facility is equipped with three observation ports, two in the sidewall and one in the rear wall, through which the burner flame can be observed or photographed. Two gas-sampling probes are used in the furnace, and three probes are used in the stack, each with three sampling ports to provide a sample representative of the stack gas. Gas samples are analyzed continuously by standard recording gas analyzers for oxygen and carbon monoxide content. However, for tests of the Todd register, gas analyses were carried out with an Orsat gas analyzer.

Back-to-back tests were run with shale DFM and with DFM. Results of these tests showed very little difference between the two test fuels.

#### Capacity Characteristics

Capacity curves for all burner combinations were determined for both fuels. Although some differences were found, the only significant difference was with the NAVJET steam atomizer, but even this was not great enough to warrant a change in atomizer size. It was concluded that an automatic combustion control system using the NAVJET steam atomizer would require recalibration for optimum fuel/air ratio, but this would not be required for control systems that use fuel flow as an index to determine required air flow.

#### Combustion Performance

Combustion performance was determined as the relation between excess air, smoke, and CO emission. The burner air flow was set at a value such that a clear stack was obtained, but a slight reduction would cause visible smoke. The percentage of excess air at this setting was determined from the stack-gas oxygen content. This procedure was carried out over a range of firing rates to plot a curve of excess air versus firing rate for the two fuels.

In tests of the Todd LVC-4M register with the NAVJET steam atomizer, it was found that shale fuel could be burned with consistently lower excess air than DFM. The difference in excess air varied from 23 percent at a low firing rate to 6.5 percent at a high firing rate. In

tests of the same register with the VP mechanical atomizer, performance was better for shale DFM at loads below 30 percent of rating, and identical for both fuels for loads above 30 percent of rating. For these tests, fuel-gas CO content was measured by an Orsat gas analyzer that cannot measure CO values below 0.1 percent (1,000 ppm).

In tests of the B&W Iowa-type register with the Racer steam atomizer, it was found that the excess air required for a clear stack was lower for shale DFM than for DFM. However, during this first use of the sensitive CO measuring instrument it was found that the CO concentration increased as excess air was reduced, and was higher at the no-smoke value of excess air for shale DFM than at the higher excess air required for smokeless combustion of DFM. The conclusion was that the optimum burner setting for best efficiency required somewhat more excess air than that for smokeless operation, and should be determined from CO concentrations instead of stack appearance.

With the VP atomizer in the Iowa register, excess air for smokeless operation was 2.5 percent lower for shale DFM than for DFM throughout the operating range, and CO was in an acceptable low range.

In tests of the CE-Wallsend air register with a CE-Wallsend steam atomizer, smoke-free combustion required less excess air with shale DFM than with DFM, but, as with other combinations, CO was higher at this lower excess air. At the highest firing rate, 2400 lb/hr, excess air was 30 percent with DFM and 10 percent with shale DFM, but the CO loss for shale DFM at this low excess air was 0.445 percent, compared with only 0.167 percent with DFM. As before, it appears desirable to set excess air on the basis of stack-gas CO level rather than stack appearance.

#### Ease of Lightoff

Ease of lightoff is determined by setting predetermined air and fuel flow rates for lightoff and performing lightoff tests. Ignition should occur within three seconds. Lightoff was quick and positive for both shale DFM and DFM. It was concluded that lightoff parameters for shale DFM were the same as for DFM.

#### Flame Stability

Flame stability was observed at both normal and abnormal conditions. The flame was found to be stable for both shale DFM and DFM under all imposed conditions. The most severe condition was that with minimum fuel flow and maximum air flow, corresponding to about 800 percent excess air.

### Flame Pattern

The flame pattern was observed for both fuels to determine that there was no flame impingement on the burner registers and furnace surfaces. Both fuels had normal flame patterns. However, the flame for the shale DFM appeared brighter and more intense than that for the DFM fuel.

### Low-Rate Operation

Each configuration was operated using both fuels at minimum fuel pressure for 4 to 6 hours to evaluate carbon buildup on the burner diffuser or refractory surfaces. No carbon buildup was observed with either fuel.

### Atomizing Steam Consumption

Both fuels were atomized satisfactorily at the lowest steam atomizing pressure, indicating no difference in steam consumption between the two fuels.

### Deleterious Effects on Burner Hardware

Throughout the test operations, atomizers, spool valves, and safety shutoff valves were inspected frequently for evidence of varnish deposits, particulate matter, or gasket material that might decompose in fuel. No deleterious effects were observed from use of shale DFM.

### Environmental Compatibility

This is concerned with effects of fuel on operators involved in changing burners, which results in direct contact of fuel with the skin. No adverse reactions to shale DFM were reported by the operators. Stack emission effects were evaluated during full-scale boiler testing later.

### Variation in Fuel Temperature

The effect of variation in fuel temperature on fuel flow rate was checked over the range from 60 F to 120 F. The effects were the same for shale DFM and DFM, and were small. With the steam atomizers the fuel flow rate decreased by 2.5 percent for each 10-degree temperature increase. For the VP atomizer, the fuel rate increased by 0.8 percent for each 10-degree rise in temperature. These atomizer characteristics have not caused problems in ships.

### Optimization of Combustion Performance

The customary method of adjusting excess air is to reduce air flow until a light haze appears, then increase air flow until the stack is clear. By this method, excess air for burning shale DFM was frequently lower than that for DFM. However, a new, sensitive CO measuring instrument revealed that the CO in the stack gas increases as excess air is reduced; at some point, the increase in CO loss exceeds the gain in excess-air loss. It appears desirable to equip ships with CO meters and use a CO criterion for adjusting burners. The potential savings is significant. This idea is to be investigated during full-scale boiler tests.

### Conclusions from Single-Burner Tests

Performance with shale DFM was satisfactory in every respect, and full-scale boiler tests are recommended.

### Full-Scale Boiler Tests (Reference 5-2)

### Boiler Descriptions

The CV-60 Class boiler is a Babcock and Wilcox Company single-furnace, single-uptake, inclined-bank natural-circulation boiler with integral superheater and extended-surface economizer. Eight boilers are installed per ship. The boiler was designed for use with Navy Special Fuel Oil and has a design pressure of 1200 psi. It was later modified for use with DFM. Boilers supply steam for ship propulsion, catapults, water distillation, and ship hotel load.

Figures 5-1 and 5-2 show the boiler arrangement, and Figure 5-3 shows the Vented Plunger mechanical atomizer used in its burners.

Table 5-1 presents design performance data for the CV-60 Class boiler. This boiler is relatively large, generating 261,450 lb steam per hour at full power.

The DDG-15 class boiler is a Combustion Engineering single-furnace, inclined-bank natural-circulation boiler with an integral superheater and extended-surface counterflow economizer. It utilizes the CE-Wallsend steam atomizing burner.

Figure 5-4 shows the arrangement of the DDG-15 Class boiler, and Figure 5-5 shows the air flow paths. The boiler has a double casing, with combustion air passing through the spaces between inner and outer casings before entering the burners. Figure 5-6 shows details of the CE-Wallsend steam atomizer.

Table 5-2 presents performance data for the DDG-15 class boiler. This is a relatively small boiler, generating 137,500 lb/hr steam at full power.

The FF-1040 class boiler is a Foster Wheeler pressure-fired (or supercharged) boiler. It is a vertical down-fired natural-circulation unit operating at 1250 psi steam pressure. The furnace pressure at full load is 68 psi. Combustion air is supplied through a supercharger unit that includes an axial-flow compressor driven by both a gas turbine and a steam boost turbine. The gas turbine is driven by boiler exhaust gas. At high loads, some exhaust gas is vented to control supercharger speed; at low loads, the steam boost turbine is used to maintain supercharger speed and flow rate. It is also used to accelerate the supercharger quickly to pick up load during rapid acceleration. The supercharger is brought up to operating speed for boiler lightoff with an electric motor.

Figure 5-7 shows the arrangement of the FF-1040 class boiler. The steam drum is mounted above the boiler, and the supercharger is above and to one side. Figure 5-8 shows gas flows within the boiler. The furnace is fired from the top, and the superheater is at the bottom behind rows of screen tubes. The boiler has no economizer; boiler exit gas temperature is reduced in expanding through the supercharger turbine, and boiler feedwater is admitted to the steam drum.

Figure 5-9 shows the CEA Combustion (formerly Todd) Triplex mechanical atomizer used in the FF-1040 class boiler. This design provides three concentric fuel nozzles, each with a separate fuel supply. The smallest is sized for boiler lightoff, at 550 psi fuel pressure, the intermediate stage provides for part-load operation, and the three stages are used together at 550 psi for full boiler load.

Table 5-3 shows design performance data for the FF-1040 class boiler.

### Test Approach

Back-to-back tests were carried out with DFM and shale DFM. Fuel samples were taken during each run and analyzed. Table 5-4 shows fuel analyses obtained. On the CV-60 class boiler, casing leakage of combustion air limited the firing rate to 100 percent of full power. On the FF-1040 class boiler, misalignment of gas path tubing caused gas inlet temperature to the superheater to reach its limit of 950 F at approximately 58 percent of full power. The DDG-15 class boiler was tested at ratings up to 120 percent of full power.

### Capacity Characteristics

Flow calibrations of the three types of fuel atomizers used in these boilers showed that capacity of the VP atomizer used in the CV-60 class boiler, and the Todd Triplex atomizer used in the FF-1040 class boiler was the same for DFM and for shale DFM. However, curves for fuel flow through the CE-Wallsend steam atomizer showed that flow of DFM and shale DFM was the same at low flow rates, but that flow of shale DFM was less at the highest flow rates. At the limiting fuel pressure of 350 psi the flow of shale DFM was 6 percent too low for full-power operation. It appears necessary to use a larger atomizer for shale DFM than for DFM.

### Combustion Performance

Combustion performance is defined in terms of the excess air needed for smoke-free combustion at each load point in the test sequence. Excess air was measured by measuring oxygen content of the stack gas. Because some inner-casing air leakage was known to exist, the absolute values of excess air are of less interest than the comparison of values for the two fuels tested. Excess air at each test point was set by adjusting the combustion airflow such that a slight decrease in airflow would cause visible smoke.

Combustion performance of the three test boilers was the same for DFM and shale DFM within experimental limits. It was concluded that differences between the two fuels are negligible, and that recalibration of the combustion controls should not be necessary except for fine tuning on an individual basis.

By use of a sensitive CO recorder in carrying out the boiler tests, it was found that the best boiler efficiency was not obtained by setting airflow by observation of stack smoke, because the CO loss might be excessive without visible smoke. It was recommended that CO meters be used aboard ship as an aid in setting optimized airflow rates. Efficiency gains ranging from 15 percent at cruising conditions to 3.5 percent at 107 percent load were predicted by changing the method of setting air flow.

### Ease of Lightoff

Quick, positive lightoff was obtained on the three test boilers with both DFM and shale DFM, using the same air and fuel rates for both fuels.

### Flame Stability

Flame stability was observed to be satisfactory at both normal and abnormal operating conditions for all boilers. Abnormal conditions were imposed by using maximum airflow and minimum fuel flows momentarily, to produce very lean combustion conditions.

### Flame Patterns

Flame patterns were observed through the small sight glass on the burner register, which gave a very limited view. No discernible differences between flame patterns when firing DFM and shale DFM were found.

### Low-Rate Operation

Each boiler was operated for 6 hours at 10 to 12 percent load, followed by furnace inspection for fireside deposits. The deposits obtained with DFM and shale DFM were similar for all boilers. The DDG-15 class and FF-1040 class boilers were clean, and moderate carbon buildup was found in the burner tile and furnace deck of the CV-60 boiler for both fuels. Minor changes in the burner register and use of a smaller fuel-nozzle orifice plate eliminate carbon buildup in the CV-60 burners.

### Effects on Burner Hardware

Throughout all operations, atomizers were inspected for potential plugging by varnish, wax, particulate matter, or gasket material. The effects of fuel on sliding spool valves was also observed. After operations representing less than 100 hours of service, no deleterious effects on the burners or fuel systems were found.

### Environmental Compatibility

During boiler operation, changing of burners by operators makes contact of fuel oil with operator skin unavoidable. No adverse reactions due to physical contact with either fuel were reported by the operators.

### Superheater Outlet Temperature

Any change in flame luminosity that changes furnace heat absorption will change gas temperature at the superheater, resulting in a change in steam temperature. No change in steam temperature was observed between DFM and shale DFM.

### Stack-Gas Temperature

Stack-gas temperatures were the same for both DFM and shale DFM.

### Flexibility Tests

A flexibility test consists of a 70 percent ramp change in boiler load, upward or downward while under automatic burner control. The maneuver should be smokeless and the flame should be stable. No difference was found between DFM and shale DFM, as both demonstrated flame stability during rapid transients.

### Fuel Analyses

Table 5-4 summarizes fuel analyses carried out for DFM and shale DFM used in the boiler tests.

### Pollutant Emissions

Pollutant emissions in boiler stack gas were measured in back-to-back tests firing DFM and shale DFM. EPA standardized instruments and procedures were used to measure carbon monoxide, nitrogen oxides, sulfur dioxide, hydrocarbons, smoke, and oxygen content of flue gas. Emission levels for these pollutants were below EPA limits for stationary sources. The differences in emissions caused by small differences in excess air from test to test overshadowed any differences attributable to the fuels. The differences in emissions between shale DFM and reference DFM appear negligible.<sup>(5-3)</sup>

### Conclusions and Recommendations

It was concluded that shale DFM of the quality used in tests of the CV-60, DDG-15, and FF-1040 class boilers can be used in USN main propulsion boilers with no adverse effects on performance. However, it will be necessary to review sizing of steam atomizers, where used, with the possibility that some will be replaced with atomizers of slightly larger flow capacity. This will also require recalibration of the combustion control.

The use of a CO instrument to determine optimum fuel-air ratios for all boilers was also recommended as a means of improving boiler efficiency. Fuel savings of up to \$16 million per year were estimated.



References

- 5-1. T. J. Ferrese, "Interim Report on Shale Fuel Oil Tests in Single Burner Test Facility", NAVSSES Project No. B-3786, 30 May, 1980.
- 5-2. T. J. Ferrese, "Test and Evaluation of Shale Fuel in Naval Combatant Type Main Propulsion Boilers", Final Report, NAVSSES Project B-3786, 15 July 1982.
- 5-3. "Evaluation of Emissions Products from the Combustion of Diesel Fuel Marine Vs. Shale Diesel Fuel in Steam Generators and Diesel Engines", Final Report, NAVSSES Project OM-0539. 30 September, 1982.

Diagram illustrating the components of a steam boiler system, showing various access points and internal structures. Key components labeled include:

- ECONOMIZER VENT CONNECTIONS
- ECONOMIZER GAS OUTLET
- ECONOMIZER ELEMENTS
- ECONOMIZER FRONT CASING
- ECONOMIZER VESTIBULE ACCESS DOOR
- SOOT BLOWER ELEMENTS
- SUPERHEATER SUPPORT TUBES
- UPTAKE SIDE OUTER CASING
- GENERATING TUBE BANK
- WATER DRUM DOWNCOMERS
- WATER DRUM
- WATER DRUM BLOWDOWN CONNECTION
- SUPERHEATER TUBES
- SUPERHEATER ACCESS DOOR
- FURNACE ACCESS DOOR
- FURNACE ROOF OUTER CASING
- AIRHEATER (ORIGINALLY USED BUT STEAM COILS NOW REMOVED)
- STEAM DRUM WITH INTERNAL DESUPERHEATER
- SATURATED STEAM OUTLET
- ECONOMIZER INLET CONNECTIONS
- SAFETY VALVE NOZZLES
- GAGE GLASS CONN.
- UPPER REAR WALL HEADER
- REAR WALL TUBES
- FURNACE SIDE OUTER CASING
- FURNACE SIDE INNER CASING
- FURNACE SIDE WALL TUBES
- SIDEWALL HEADER BLOWDOWN CONNECTIONS
- SIDEWALL FRONT OUTER CASING
- BOILER FRONT INNER CASING
- AIR REGISTER OPENING
- INSPECTION LIGHT (MIL. P. 18377/28)
- OIL LEAKAGE OBSERVATION PORT

FIGURE 5-1. BABCOCK AND WILCOX CV-60 CLASS  
NATURAL CIRCULATION BOILER (5-2)

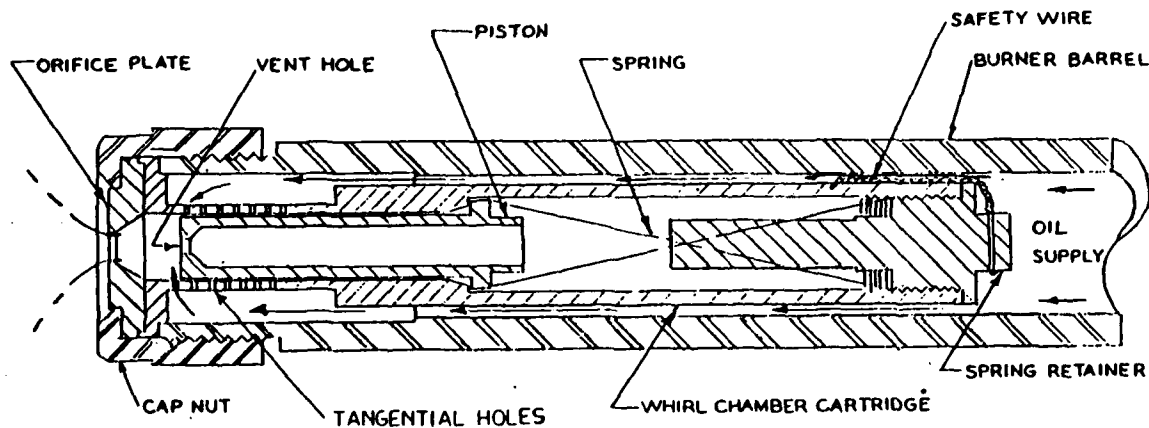


FIGURE 5-3. CROSS SECTION OF VENTED PLUNGER ATOMIZER<sup>(5-2)</sup>

TABLE 5-1 DESIGN PERFORMANCE DATA FOR B&W CV-60 CLASS BOILER<sup>(5-2)</sup>

	FULL POWER	OVERLOAD
Rate of Operation, percent	100	120
Total Steam Generated, lb/hr	261,450	313,800
Superheated Steam, lb/hr	226,550	250,980
Boiler Drum Pressure, psig	1290	1330
Superheater Outlet Pressure, psig	1200	1200
Superheater Outlet Temperature, °F	950 min 1000 max	950 min
Desuperheater Outlet Pressure, psig	1180	-
Desuperheater Outlet Temperature, °F	634 @ 34,900 pph	-
Economizer Inlet Temperature, °F	246	-
Economizer Outlet Temperature, °F	433	-
Boiler Air Inlet Temperature, °F	100	68
Total Air Flow, Cu Ft/Hr/lb oil	240	260
Total Oil Flow, lb/hr	20050	24720
Number of Burners in Operation	7	7

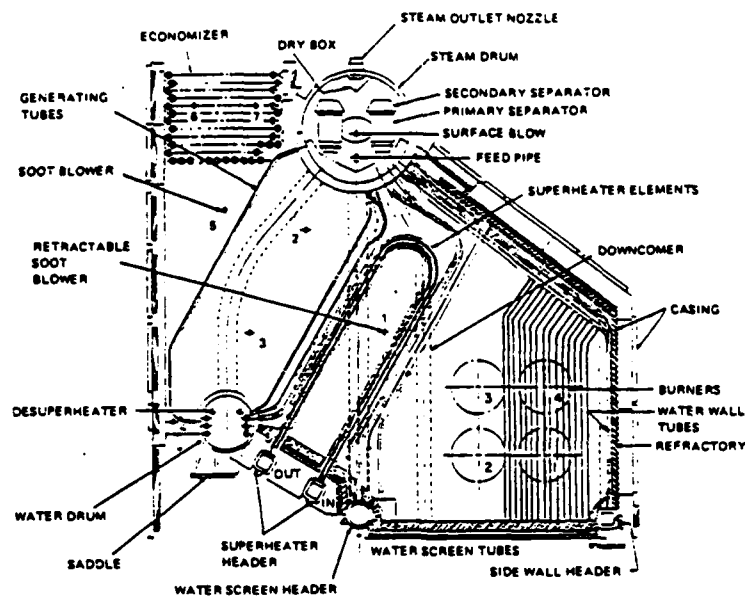


FIGURE 5-4. COMBUSTION ENGINEERING, INC. DDG-15 CLASS<sup>(5-2)</sup>  
NATURAL CIRCULATION BOILER

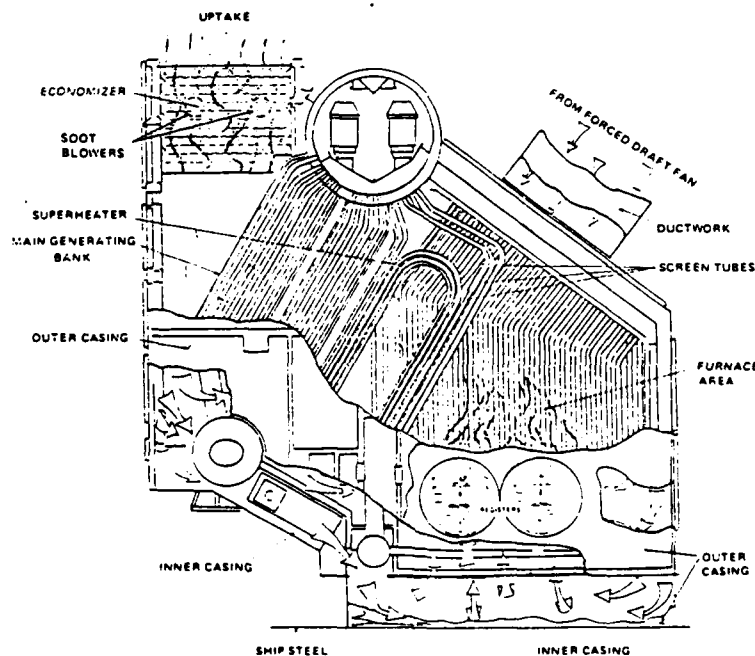


FIGURE 5-5. AIR AND GAS FLOW PATHS IN DDG-15 CLASS BOILER<sup>(5-2)</sup>

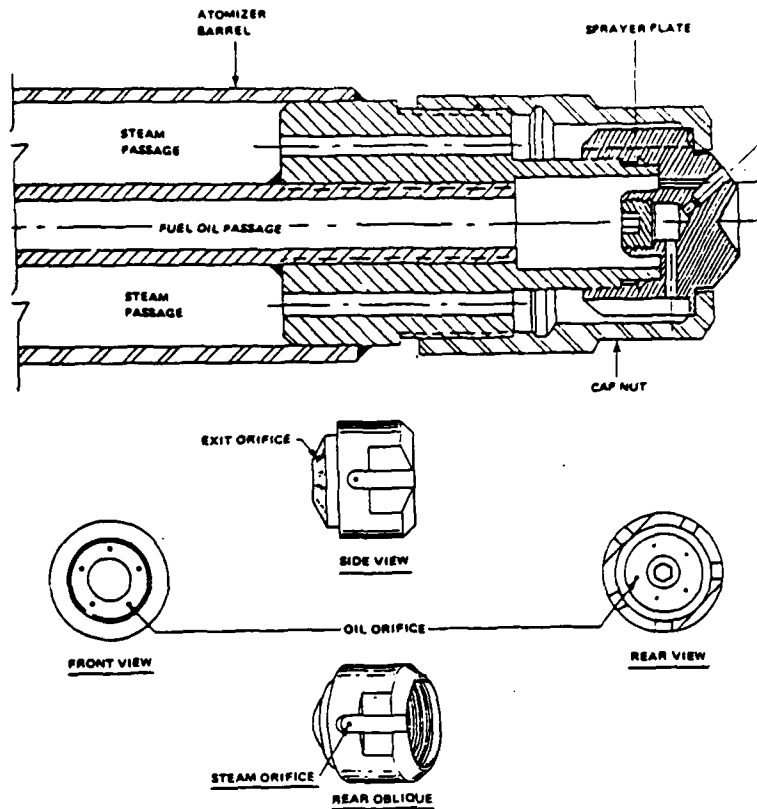


FIGURE 5-6. COMBUSTION ENGINEERING WALLSEND STEAM ATOMIZER<sup>(5-2)</sup>

TABLE 5-2. DESIGN PERFORMANCE DATA FOR DDG-15 CLASS BOILER<sup>(5-2)</sup>

	10 PERCENT	CRUISING	FULL POWER	OVERLOAD
Rate of Operation, percent	10	39.2	100	120
Total Steam Generated, lb/hr	13,750	54,600	137,500	165,000
Superheated Steam, lb/hr	8,750	47,700	120,400	131,900
Boiler Drum Pressure, psig	1275	1275	1275	1275
Superheater Outlet Pressure, psig	1275	1265	1200	1165
Superheater Outlet Temperature, °F	870	940	950	925
Desuperheater Outlet Pressure, psig	1270	1260	1175	1065
Desuperheater Outlet Temperature, °F	645	653	690	700
Economizer Inlet Temperature, °F	246	246	246	246
Economizer Outlet Temperature, °F	430	405	440	440
Burner Air Inlet Temperature, °F	100	100	100	100
Total Air Flow, lb/hr	26,800	68,100	176,800	217,000
Total Oil Flow, lb/hr	1,058	4,125	10,980	13,160
Anticipated Efficiency, percent	81.0	87.5	83.5	82.2
Excess Air, percent	80	18.5	15	18.5
Number of Burners in Operation	4	4	4	4
Stack Gas Temperature, °F	285	355	545	595

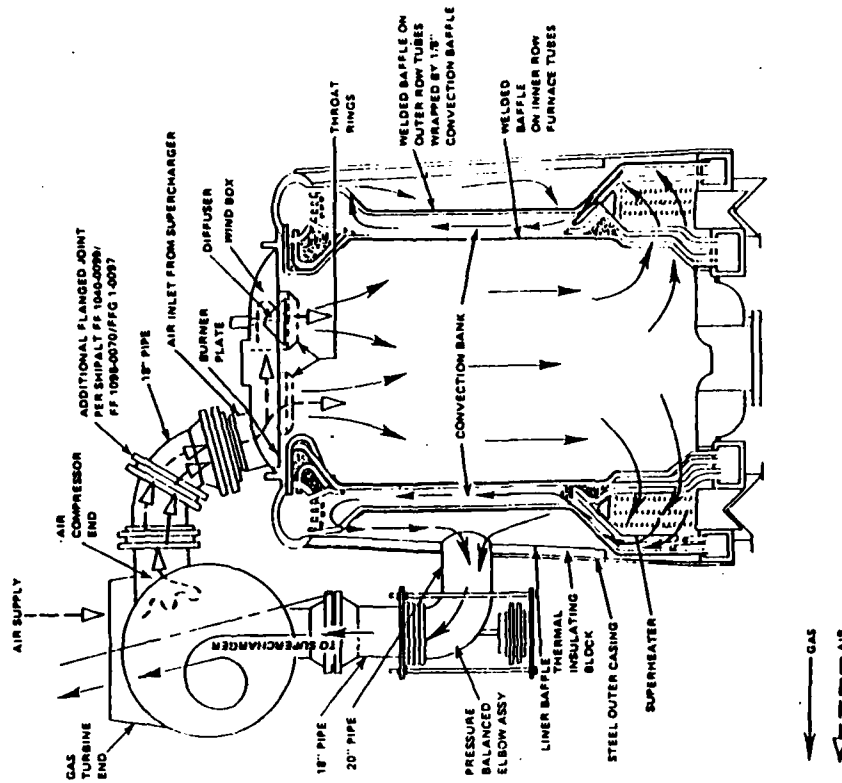


FIGURE 5-8. AIR AND GAS FLOW PATHS IN  
FF-1040 CLASS BOILER (5-2)

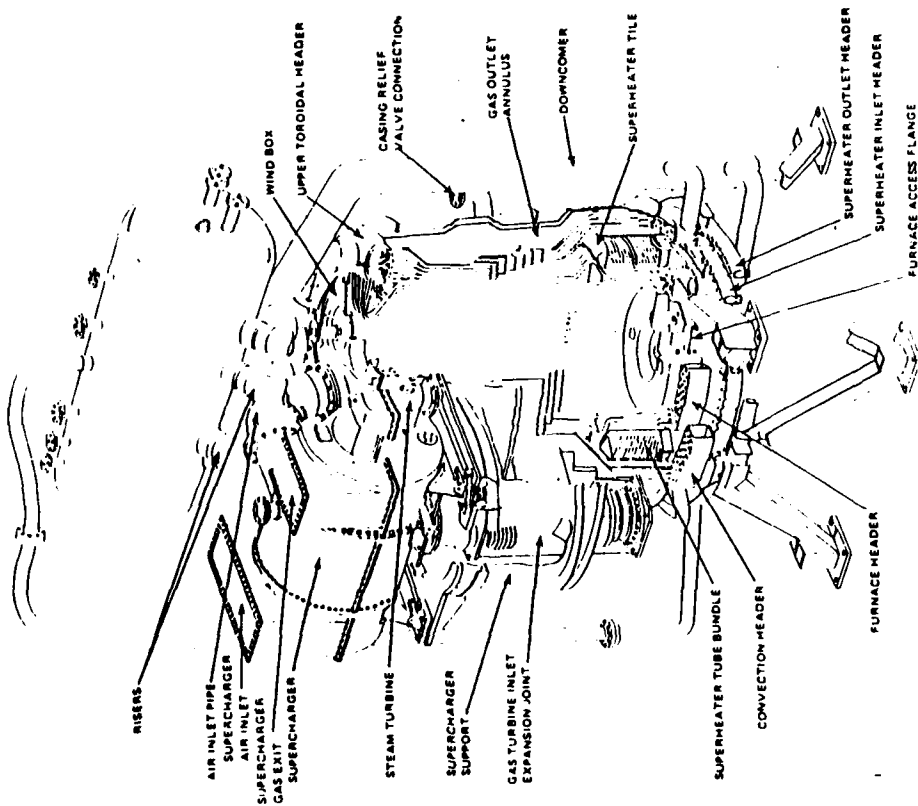
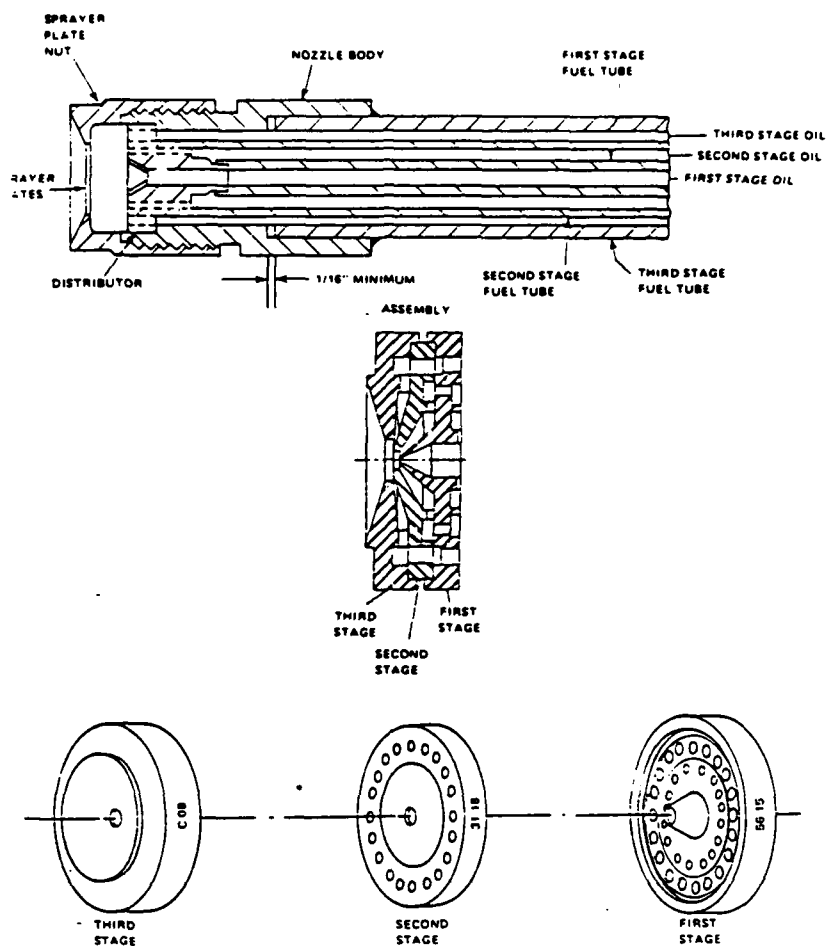


FIGURE 5-7. FOSTER WHEELER FF-1040 CLASS  
PRESSURE FIRED BOILER (5-2)

FIGURE 5-9. TODD TRIPLEX MECHANICAL ATOMIZER<sup>(5-2)</sup>TABLE 5-3. DESIGN PERFORMANCE DATA, FF-1040  
CLASS PRESSURE FIRED BOILER<sup>(5-2)</sup>

	<u>CRUISING</u>	<u>FULL POWER</u>	<u>OVERLOAD</u>
Rate of Operation, percent	41	100	117.2
Total Steam Generated, lb/hr	51,900	126,410	148,100
Superheated Steam, lb/hr	44,400	116,330	132,260
Boiler Drum Pressure, psig	1250	1250	1250
Superheater Outlet Pressure, psig	1240	1200	1180
Superheater Outlet Temperature, °F	950	960	937
Desuperheater Outlet Pressure, psig	1230	1185	1135
Desuperheater Outlet Temperature, °F	635	680	710
Feedwater Inlet Temperature To Drum, °F	240	240	240
Burner Air Inlet Temperature, °F	287	485	565
Total Air Flow, lb/hr	61,740	153,410	176,010
Total Oil Flow, lb/hr	3,920	9,740	11,175
Anticipated Efficiency, percent	80.9	83.2	83.3
Excess Air, percent	13	13	13
Number of Burners in Operation	3	3	3
Supercharger Gas Inlet Temperature, °F	750	870	915
Supercharger Gas Outlet Temperature, °F	535	480	475
Supercharger Speed, RPM	5400	8750	9550

TABLE 5-4. ANALYSES OF FUELS USED IN BOILER TESTS<sup>(5-2)</sup>

FUEL TYPE BOILER DATE	SHALE				DFM			
	CTF	DDG-15	PFB	CV-60	CTF	DDG-15	PFB	CV-60
	8/79	8/80	9/80	1/81	9/79	8/80	10/80	5/80
<u>TEST</u>								
Atmospheric Distillation; °F ASTM D 86								
IBP	408	398	390	395	372	380	382	395
50X	510	510	506	508	502	506	512	522
90X	564	565	561	560	594	606	600	594
E.P.								
Viscosity; CS @ 100°F ASTM D445	2.91	2.71	2.80	2.82	2.87	2.73	2.85	3.25
API Gravity; 60°F ASTM D287	37.7	37.8	37.6	37.8	35.2	34.0	34.6	35.1
Flash Point; °F ASTM D93	190	172	173	175	177	175	178	185
Sediment; mg/l ASTM D2276	-	5.9	5.6	6.8	-	28.7	20.0	-
Total Water; % ASTM D1744	-	0.02	0.02	0.01	-	0.01	0.01	0.01
Higher Heating Value; BTU/lb ASTM D2718	19750	19770	19760	19770	19600	19550	19580	19590
<u>COMPOSITION; %</u>								
Carbon	86.7	86.6	86.8	86.8	86.4	86.7	86.6	86.5
Hydrogen	13.0	13.2	13.0	13.0	12.9	12.8	12.9	13.0
Nitrogen	0.01	0.01	0.01	0.01	0.08	0.06	0.06	0.06
Sulfur	0.02	0.01	0.01	0.01	0.16	0.16	0.15	0.19
Oxygen & Undetermined	0.27	0.18	0.18	0.18	0.46	0.28	0.27	0.25



6. DETROIT DIESEL ALLISON TESTS OF MODEL  
501-K17 GAS TURBINE  
(Reference 6-1)

Summary

A test program was conducted at the Detroit Diesel Allison Research and Engineering Center, Indianapolis, Indiana, to evaluate the effects of shale-derived DFM on the performance, emission, and endurance characteristics of the Model 501-K17 engine. The Detroit Diesel Allison Model 501-K17 is the gas turbine engine that provides power for the ship-service generators aboard the U.S. Navy DD963-class (Spruance-class), DDG993-class (Kidd-class), and CG47-class (Ticonderoga-class) ships.

Performance, operating characteristics, emissions, and combustor metal temperature data were obtained during single-burner rig and engine testing. Combustion ignition and lean blowout limits at ambient conditions were also determined during single-burner rig testing. Rig and engine data were obtained in back-to-back tests with DFM and shale DFM.

In addition, the longer term effects of operating the Model 501-K17 engine on shale DFM were evaluated with a 1000-hr endurance test following a typical DD963 duty cycle.

The conclusion reached was that Model 501-K17 engines in the fleet can operate satisfactorily without operational, performance, or endurance penalty from operating on shale DFM of the quality used for this test program.

Approach

The 501-K17 test program included two phases. Phase 1 was a single-burner rig test to obtain detailed information on combustor performance with shale DFM and DFM. It was run at full engine pressure and temperature conditions. Phase 2 was an engine endurance test in which the engine was operated for 1,000 hr following a 24-hr cycle of varying load that included a shutdown of 3 hr after each cycle. The engine performance and emissions on both shale fuel and DFM were characterized before and after the endurance test. At the conclusion of the endurance test the engine was torn down and inspected in detail, and found to be in good condition.

Engine Description

The Model 501-K17 is a gas turbine engine produced by Detroit Diesel Allison (DDA) for powering ship-service generators aboard U.S. Navy ships of the DD963, DDG993, and CG47 classes. It is a single-shaft

engine with a 14-stage axial-flow compressor directly coupled to a 4-stage air-cooled turbine, with a pressure ratio of 8.5 at a rated speed of 13,820 rpm. It has six can-type combustion chambers in an annular casing. The five main bearings are Grade 5 antifriction bearings cooled and lubricated by a pressure-lubricating system. Its nominal power output for Navy service is 2850 hp.

### Fuel Analyses

Two fuels were used during this evaluation. The shale DFM was supplied to Allison by the U.S. Navy Energy Research and Development Office of DTNSRDC and stored in newly cleaned underground storage tanks. The DFM was purchased by DDA to specification MIL-F-16884G. The DFM was used to provide baseline data for evaluating performance, smoke, emissions, and combustor metal temperatures.

Table 6-1 summarizes analytical data for both the shale DFM and the DFM. The analyses were performed by the DDA laboratories except for measurement of gross heat of combustion by bomb calorimeter, and elemental analyses for carbon, hydrogen, oxygen, and nitrogen; these were performed by Gulf Research and Development Company, Pittsburgh, Pennsylvania. It is evident from Table 6-1 that the shale fuel meets all requirements for DFM, MIL-F-16884G.

Two shipments of shale DFM were received from the Navy. The first shipment, of 126,545 gallons, was received in March, 1979, and the second shipment, of 88,053 gallons, was received in March, 1981.

### Single-Burner Rig Tests

The tests with the single-burner rig were conducted 19 August 1980 through 4 November 1980 to compare the combustion characteristics of shale DFM with those of DFM prior to full engine testing. The single-burner rig simulated the conditions of one of the six combustors of the Model 501-K17 engine.

The conclusions reached from the rig testing indicated that no problem would exist during engine testing with the shale DFM and that performance with shale DFM would be essentially the same as with DFM.

### Arrangement of Burner Test Rig

Figure 6-1 shows the arrangement of the burner test rig and its instrumentation. The combustion air passes through a diffuser section duplicating the engine contours, through a section duplicating the engine combustor inner and outer case contours containing a production 501-K17 combustor, and exits through a simulated turbine inlet section containing an array of combustor outlet instrumentation

probes. An exhaust valve simulated the turbine pressure drop, thus maintaining the combustor section of the rig at engine operating pressure levels. The fuel nozzle and igniter were located as they are in the engine and were production parts.

The test rig simulated combustor inlet and exit conditions to the extent possible with an exact-dimension 60-degree engine segment. Non-vitiated air was supplied to the test combustor at mass flow rates, temperatures, and pressures matching those of the engine at various loads. A remote computerized data acquisition and reduction system was used for logging data.

The test rig and test cell included instrumentation used to measure and record the following:

- o Combustor airflow
- o Combustor inlet air temperature
- o Combustor inlet air total pressure
- o Combustor fuel flow
- o Combustor outlet temperature (10 rakes with 3 elements each, as shown in Figure 6-1 these were used to obtain the temperature pattern and "hot spot" as well as the average temperature)
- o Combustor outlet total pressure (two total pressure probes are located within the thermocouple array at the radial centerline of the duct)
- o Combustor wall temperatures
- o Emissions of  $\text{NO}_x$ , CO,  $\text{CO}_2$ , smoke, and unburned hydrocarbons.

Smoke and gaseous emission measurements are made with exhaust gas withdrawn at ten circumferential positions alternately spaced with respect to the outlet temperature probes. The exhaust gas line to the emission measuring equipment is maintained at 300 F. The smoke density is quantified by reflectance measurements of a filter stain. Each value reported represents the average of three determinations at the test point. On-line exhaust gas emission determinations were performed using standard recording analyzers.

Combustor wall metal temperatures were taken at 12 locations. Since one objective of the test was to assess the change in combustor metal temperature (a life prediction measure) with a change from DFM to shale DFM, it was desired to locate the thermocouples in the most likely high-wall-temperature areas. To identify these locations, a thermal paint test was conducted with DFM fuel. The production Model 501-K17

combustor was coated with TP-8 paint. It was then tested for 30 minutes at conditions that simulated 100 percent power operation with 14th-stage air bleed. After the combustor was removed from the rig, it was marked to clearly define the isotherms and then photographed. From a study of the combustor and the photographs, the wall thermocouple locations were selected and twelve chromel-alumel thermocouples were installed at the points of highest temperature indicated by the thermal paint tests.

### Test Configuration

The engine parts installed in the single-burner rig were the following current production Model 501-K17 parts:

- o Combustor, P/N 6887756, S/N AA01099
- o Dual entry fuel nozzle, P/N 6899300, S/N AG52382
- o Fuel flow divider, P/N 6899760, S/N 60082
- o Igniter, P/N 6847727A
- o Exciter, P/N 6870592.

The combustor was one of six new combustors obtained for the engine test. The fuel nozzle was also a new part obtained for this test. The fuel nozzle and flow divider were both flow bench tested with MIL-C-7024 Type II test fluid prior to any rig testing to provide a flow calibration and to ensure that the flow characteristics were within specification. Both were within specification.

### Ignition Test

Ignition tests were conducted with ambient inlet air to determine the minimum fuel flow required for ignition. Both shale DFM and DFM fuels were tested at five different airflows ranging from 0.4 to 2.0 lbm/sec (0.18 to 0.91 kg/s) at ambient air inlet temperatures.

The results indicated that slightly higher fuel/air ratios were required for ignition with shale DFM than with DFM. The results are shown in Figure 6-2. The small differences noted were not expected to have an adverse effect on the starting capability of the engine.

### Lean Blowout Test

Lean blowout testing was conducted to determine the lower limit of fuel/air ratios that would support combustion. Again, both shale DFM and DFM fuels were tested at five different airflows ranging from 0.4 to 2.0 lbm/sec (0.18 to 0.91 kg/s) at ambient air inlet temperatures.

The results indicated that the lean blowout limits were higher for the shale DFM only at the lower airflows. At the higher airflow

conditions of the test there was essentially no difference. The results are shown graphically in Figure 6-3. From these lean blowout data it was not expected that the operation of the engine would be adversely affected during deceleration transients.

#### Performance Test

Table 6-2 lists rig test conditions. Combustor performance was tested at six rig conditions representing the conditions to which the combustor is exposed. Five of the conditions were with airflows representing no 14th-stage compressor air bleed. The sixth condition represented 100 percent power operation with 14th-stage compressor air being bled. The Navy uses this 14th-stage air for nonengine purposes. At all conditions a small amount of air was bled to simulate the air used for turbine cooling and labyrinth seal pressurization.

Combustion section performance comparisons between DFM and shale DFM included comparisons of calculated combustion efficiency and measured outlet temperature profiles.

Figure 6-4 shows that calculated combustion efficiency was slightly higher for single burner rig operation with DFM than with shale DFM. The difference was approximately 0.1 percent.

Figure 6-5 compares outlet pattern factors for DFM and shale DFM. This is a measure of combustor performance. The higher the pattern factor, the higher the measured maximum outlet temperature (or hot spot), which in turn can adversely affect turbine life. As shown in Figure 6-5, the pattern factor differed very little with operation at all power conditions from 25 percent up through 100 percent with bleed. The patterns are almost identical with DFM and shale DFM.

#### Wall Temperatures

Figure 6-6 shows combustor wall temperatures. The wall or combustor metal temperatures were essentially the same with shale DFM as with DFM. The data shown are for the 100 percent plus bleed condition and for the 25 percent power condition, which are the highest and lowest wall temperatures of the test. The wall temperatures are essentially the same for both fuels. This was also true for the conditions between the two extremes.

#### Emissions and Smoke

Figure 6-7 shows the measured smoke values obtained during operation with shale DFM and with DFM which were essentially identical.

Figure 6-8 shows the results of the hydrocarbon ( $HC_x$ ) emission measurements. The  $HC_x$  measurements were consistently higher for shale DFM than for DFM during the rig tests.  $NO_x$  emissions were the same for both fuels.

#### Post-Test Parts Condition

The engine parts used in the rig tests were examined after the use of each fuel and the results documented.

Neither fuel left a significant carbon residue on the inside of the combustor. However, following operation with the shale DFM the inside of the combustor was noticeably cleaner than with the DFM. The same relationship was observed when examining the fuel nozzle for carbon deposits. The deposits were noticeably less with the shale DFM. However, the deposits with DFM, while comparatively greater, were minor and would not cause a fuel nozzle problem.

The fuel nozzle and fuel flow divider valve were both bench-test calibrated after the rig testing. The test fluid used for the standard calibration procedure was MIL-C-7024 Type II test fluid. The flow characteristics of both were within specification and virtually unchanged from the pretest calibration.

#### 501-K17 Engine Test

Engine tests were conducted to determine comparative performance, smoke, emissions, and combustor wall metal temperatures during engine operation with shale DFM and with DFM. Engine endurance testing for 1000 hr was conducted with 194,371 gallons of the 214,598 gallons of shale DFM delivered by the Navy. A comprehensive post-test inspection was performed to determine how the use of shale DFM affected engine parts.

The results of the engine tests showed that there was no adverse effect from the use of shale DFM as the fuel. Based on the results of all aspects of the engine testing phase (as well as the prior rig testing), the 501-K17s in the fleet can operate satisfactorily without operational, performance, or endurance penalty from using shale-derived fuel of the quality used for this program.

#### Description of Test Engine

The engine configuration tested conformed to the 501-K17 production configuration in those areas that could be affected by or could affect the fuel handling and combustion process with shale DFM. Specifically, these were as follows.

AD-A145 159

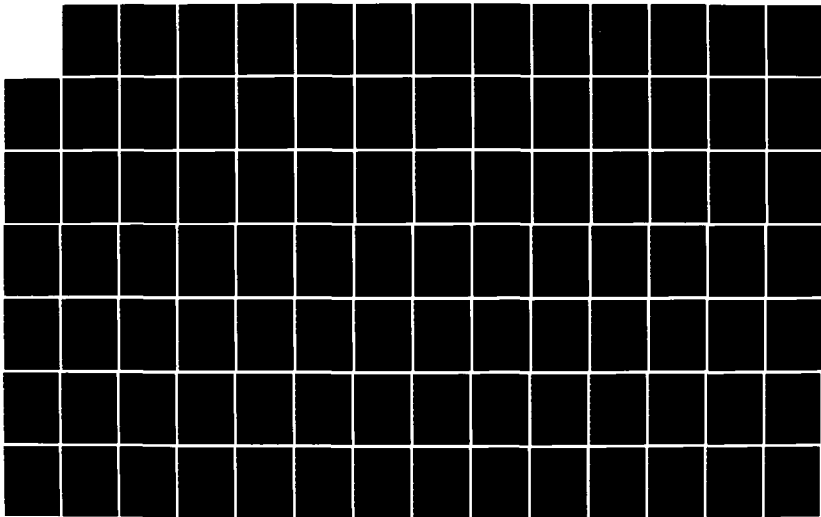
JOINT DOD/DOE SHALE OIL PROJECT VOLUME 3 TESTING OF  
REFINED SHALE OIL FUELS(U) BATTELLE COLUMBUS LABS OH  
H R HAZARD ET AL. DEC 83 N00014-83-C-0156

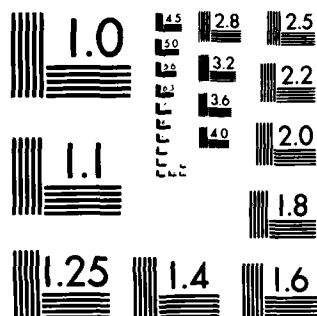
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Combustors. Five of the six combustors were the standard 501-K17 production type, P/N 6887756. The sixth combustor was one incorporating some new features. This one was in the process of being released as a superseding 501-K17 combustor. With the incorporation of this newer version, any effect of shale DFM use could be determined on current and future combustors. Two of the standard production combustors were instrumented with 12 thermocouples each. One of these was the same combustor used in the rig test.

Fuel Nozzles. The fuel nozzles, DDA P/N 6899300, S/N AG52374 through S/N AG52379, were the latest 501-K17 dual entry type with which the fleet engines were being refitted.

Turbine. All blades and vanes of the turbine were standard production part numbers. In addition, new blades and vanes were installed for the first and second stages. Thus, if any erosion were to occur, it could be easily identified and related to the shale DFM test and not any earlier testing.

Fuel Pump. A standard fuel pump was provided by Sundstrand, the manufacturer, who carried out detailed inspection and measurement of pump parts, and a quantitative capacity calibration, before and after the endurance test.

Non-Standard Components. The 1,000-hr endurance test was used as an opportunity to test several new engine components, including a turbine temperature thermocouple monitor and spread alarm system, a new turbine stationary front labyrinth seal member, a new front compressor seal, new combustor crossover tube clamps, and a fuel valve with a revised fuel schedule that had been released in May, 1981. These components had been developed under the component improvement contract.

### Engine Test Setup

The endurance testing with Allison engine S/N ASP002 was conducted at the Plant No. 8 powerhouse. The engine was installed as a part of a generator set. The generator set included the engine; a direct coupled Falk reduction gearbox; and a 4160-volt, 900-rpm Electromotive GMC generator rated at 2500 kW. A Bendix Model 36E91-6 air turbine starter mounted on the Falk gearbox and using 50 psig (344.7 kPa) inlet pressure air was used for engine starting. A wing face and bypass type steam coil was used to heat the engine inlet air and maintain the required 100 F (38 C) inlet temperature. A temperature sensing bulb installed in the air inlet duct pneumatically controlled the position of the heater bypass louvers to maintain the desired air temperature. A valve in the louver control line allowed manual opening of the louvers to full bypass position during down periods to prevent heat buildup in

the filter house. The power output was measured by the installed watt meter. The pressure and temperature instrumentation was calibrated prior to the test. The emission measurement instrumentation was the same as that used for rig testing.

### Performance Tests

Prior to endurance testing and again following endurance testing, installed engine performance calibration tests were conducted with shale DFM and with DFM. Performance characteristics at the required 0 percent, 25 percent, 50 percent, 75 percent, and 100 percent power levels and a 100 percent power with 14th-stage bleed were obtained from a seven-point calibration. Performance test calibration data were recorded manually and included the following:

- o Engine, rpm (constant 13,820)
- o Engine load, kW (varied per schedule)
- o Compressor inlet temperature (constant 100 F (38 C))
- o Turbine inlet temperature (varied with load)
- o Fuel flow (varied with load)
- o Fuel temperature (varied)
- o Compressor inlet pressure (varied with engine and ambient conditions)
- o Exhaust static pressure (varied).

Performance data were obtained daily throughout the endurance test to detect any unexpected change in performance.

### Emissions Tests

Emissions data were obtained prior to endurance testing and following endurance testing at each of the performance measurement conditions with shale DFM and with DFM. Exhaust gas was flowed continuously from the engine to the emission measuring equipment. The exhaust gas line was maintained at 300 F (149 C). The smoke values reported represent an average of at least three readings. The smoke density was quantified by reflectance measurements of a filter stain. Gaseous emissions were measured continuously. Each gas analysis value reported represents the stabilized value obtained, generally from a minimum of 5 minutes of continuous analysis.

### Endurance Test Cycle

The 1,000-hr endurance test was carried out by repeating a 7-hr test cycle shown in Table 6-3. This is the standard test cycle used to qualify the 501-K17 engine, as established by DDA and NAVSEA for the initial engine qualification. The test was run by repeating this 7-hour cycle three times, then shutting down for 3 hours. During the shutdown

period three starts were made, one being the start of the next 24-hr cycle. Thus three starts and 21 hours of operation were obtained during each 24-hr cycle. The 1,000-hr test would require 42 such 24-hr cycles.

Borescope inspections were performed at 100 hr, 200 hr, and 400 hr by removing fuel nozzles to view combustor liners and first-stage turbine nozzles. At 576 hr the test was interrupted to replace an engine accessory gearbox bearing that had started to spall.

During the endurance test the turbine was loaded by paralleling the generator with local utility service lines. An automatic turbine inlet temperature controller maintained proper temperature levels and changed these levels to follow the test cycle. Operating personnel were needed only for starts, shutdowns, compressor bleed operation, and performance monitoring.

#### Post-Test Walnut-Shell Compressor Cleaning

Following the post-endurance performance test, the compressor was cleaned by introducing ground walnut shells of the approved type into the compressor. The performance test was repeated with DFM to determine the gain from the cleaning.

At the conclusion of testing the engine was removed to the assembly area, disassembled, and subjected to a detailed inspection.

### Test Results

#### Engine Operating Notes

During the engine testing no operating problems were encountered due to the use of the shale DFM. No special parts were installed and no special adjustments were required to operate satisfactorily on shale DFM. There was no problem with starting, transient, or general operation. Individual combustor outlet average temperature differences from highest to lowest remained at approximately 60 F (15.5 C) throughout the test. All special features that were incorporated into the engine to obtain endurance experience performed satisfactorily.

#### Performance

Figure 6-9 compares pre-endurance performance for shale DFM and DFM. There was essentially no difference in performance with the two fuels. At the higher operating temperatures the shaft power output was slightly less with shale DFM but the fuel flow recorded was also slightly less.

Figure 6-10 compares post-endurance performance for shale DFM and DFM. There were slight differences in both shaft output power and fuel flow--about the same as noted prior to endurance. Also shown by Figure 6-10 was the effect of walnut-shell cleaning of the compressor at the end of the post-endurance performance testing. A performance calibration was made with DFM after the cleaning. The performance gain from the cleaning, shown in Figure 6-10, is consistent with previous cleaning gains on other engine tests.

The performance testing indicated clearly that there was no adverse effect on performance as a result of the 1000 hr of operation with shale DFM.

#### Combustor Wall Temperatures

Figure 6-11 shows combustor wall temperatures from the two instrumented combustors for the most extreme condition, 100 percent power plus bleed. Some of the thermocouples did not survive the pre-endurance testing. There was very little difference in the data between fuels with the same combustor. There was a much greater difference between combustors, especially at the fourth, fifth, and sixth thermocouple locations.

Figure 6-12 is a comparison of data from the rig and from the engine tests with the same combustor. A shift in the peak temperature location from the fifth position on the rig to the third position on the engine was noted. However, both these locations are just aft of the crossover tubes between combustors and are located in an expected distress area based on both experience and the earlier thermal paint test.

#### Emissions and Smoke

Figure 6-13 shows the measured smoke values obtained during the engine pre-endurance and post-endurance performance calibrations. During the pre-endurance testing, operation with shale produced slightly less smoke than did DFM (lower set of curves). During the post-endurance testing, the values with the two fuels were essentially the same (upper set of curves). From the test data curve it appears that the DFM and shale pre-endurance and post-endurance tests would have met the engine specification 828-D requirement of a maximum SAE smoke number of 23.5 ft at 2680 kW if a load that high had been included in the test schedule. However, there was a significant difference between the pre-endurance and post-endurance values. The post-endurance values were verified by a retest, but the reason for the difference is not known. The increase of approximately 10 smoke numbers is somewhat greater than previously seen when endurance tests were conducted with petroleum-based fuel. Prior tests showed an increase of approximately 7-8 smoke numbers.

Figure 6-14 shows the HC<sub>x</sub> emission values. The trend exhibited during the engine tests (both pre-endurance and post-endurance) was the same as during the rig test. The HC<sub>x</sub> concentration was higher for shale DFM than for DFM. The values for both fuels were slightly higher after the endurance testing than before.

Figure 6-15 shows NO<sub>x</sub> emission values. Although slightly higher values were recorded during the pre-endurance compared with post-endurance testing, there was essentially no difference between values obtained with shale DFM and DFM.

Figure 6-16 shows the CO emission values. There was a slight difference noted in CO values at the lower engine loads. However, as the load was increased the values were essentially the same.

#### Post-Test Inspection

Following completion of all tests the engine was disassembled and inspected. The general condition of the engine was excellent. Although there was local distress in a few areas, the parts were in better condition than were the parts from a similar engine tested previously to the same test schedule for 500 hours on DF-2.

Combustors. Inspection of the combustors showed that some local warpage and cracking had occurred, similar to that for previous DF-2 tests. The combustor in the second position had a collapsed internal cooling baffle; this did not occur in the combustor in the fifth position, which contained an experimental cooling air baffle made of etched, transpiration-cooled metal. The combustor in the fourth position developed some warpage, and some cracks developed near the crossover ferrule. This condition has occurred in previous tests and is not related to shale fuels.

Turbine. The turbine was in excellent condition after the tests. There was no evidence of erosion or corrosion of turbine blading.

Fuel Nozzles. The fuel nozzles and flow dividers calibrated within specifications before and after the test, and no problems were encountered during the test.

Fuel Pump. No problems were encountered with the fuel pump during the test. The pump (Sundstrand P/N 022489-054) S/N 10090T was returned to Sundstrand, where it was retested, disassembled and inspected. The inspection and calibration showed that calibration was

unchanged, there was slight evidence of cavitation on pumping elements, slight wear of splines, and the bearings and O-rings were excellent.

#### Conclusions

It was concluded that the Model 501-K17 engines in the fleet can operate satisfactorily without penalizing operation, performance, or endurance when using shale DFM of the quality used for this test program.

#### References

- 6-1. Hillery, R. D., "Navy Shale Oil Test Program for Model 501-K17 Gas Turbine Engine". Final Report by Detroit Diesel Allison to DTNSRDC, November 1982 Report No. DTNSRDC-PASD-CR-10-82.

TABLE 6-1. PROPERTIES OF SHALE DFM AND PETROLEUM DFM USED IN TESTS<sup>(6-1)</sup>

Properties	Shale DFM	Petroleum DFM	Spec MIL-F-16884C
Distillation			
Initial boiling point--°F	390	357	--
5% recovery--°F	435	400	--
10% recovery--°F	450	410	--
20% recovery--°F	471	421	--
30% recovery--°F	484	434	--
40% recovery--°F	496	445	--
50% recovery--°F	507	456	--
60% recovery--°F	519	468	--
70% recovery--°F	530	481	--
80% recovery--°F	544	503	--
90% recovery--°F	560	544	675 max
95% recovery--°F	571	579	--
End point--°F	583	603	725 max
Recovered--%	98.0	97.9	--
Residue--%	1.4	1.6	--
Loss--%	0.6	0.5	--
Residue + loss--%	2.0	2.1	3.0 max
Color	0	4.5	5 max
Gravity, API	37.9	37.8	--
Specific gravity, 60/60°F	0.8353	0.8358	--
Sulfur--% by wt	0.005	0.08	1.00 max
Net heat of combustion, Btu/lb**	18,358	18,463	--
Aniline point--°F	149.7	138.6	--
Smoke point--mm	14.3	14.3	--
Flash point--°F	168	121	140 min
Corrosion, copper strip	1 b	1 a	1 b max
Pour point--°F	-5	-35	20 max
Cloud point--°F	0	-14	30 max
Viscosity at 100°F, cs	2.71	1.99	1.8-4.5
Viscosity at 32°F, cs	7.19	4.57	--
Cetane number	54.5	45.5	45 min
Ramsbottom carbon residue on 10% bottoms--% by wt	0.09	0.34	0.20 max
Ash--% by wt	0.005	0.005	0.005 max
Demulsification--minutes	8	8	10 max
Acid No.--mg KOH/g	0.03	0.03	0.30 max
Neutrality	Neutral	Neutral	Neutral
Accelerated stability, total insolubles--mg/100 mL	0.03	0.4	2.5 max
Particulates--mg/L	0.6	5.6	--
Water and sediment--% vol	<0.025	<0.025	--
Aromatics--% by vol	22.9	22.4	--
Olefins--% by vol	8.0	3.2	--
Carbon--% by wt***	86.3	86.50	--
Hydrogen--% by wt***	13.42	13.17	--
Oxygen--ppm***	<100	<100	--
Nitrogen--ppm***	4.3	142	--
Gross heat of combustion-- Btu/lb**	19,664	19,544	--

\*All properties determined at DDA in September 1980 unless otherwise noted.

\*\*Based on gross heat of combustion data obtained with a bomb calorimeter by Gulf Research and Development Company, 10 September 1980.

\*\*\*Determined by Gulf Research and Development Company, 10 September 1980.

Metric conversions: °C = (°F-32)/1.8  
MJ = 0.002 326 Btu/lbm

TABLE 6-2. TEST CONDITIONS FOR COMBUSTOR TEST RIG<sup>(6-1)</sup>

Nominal engine condition	Burner inlet pressure --psia	Burner inlet temp-- °F	Rig airflow --lb/sec	Bleed airflow --lb/sec	Liner airflow --lb/sec	Fuel* flow --lb/hr	Burner outlet temp-- °F
<u>No 14th-stg bleed</u>							
100% power, 2937 shp	118.8	641	4.862	0.284	4.578	280.0	1736
75% power, 2203 shp	114.8	631	4.872	0.285	4.587	235.0	1565
50% power, 1469 shp	110.7	622	4.882	0.285	4.597	191.7	1395
25% power, 734 shp	106.2	613	4.889	0.285	4.604	148.3	1223
0% power, 100 shp	102.0	606	4.892	0.286	4.606	33.3	1070
<u>14-stg bleed</u>							
100% power, 2877 shp	113.1	628	4.760	0.285	4.475	306.7	1910

\*Based on lower heating value (LHV) = 18,400 Btu/lb

$$W_{f, \text{actual}} = W_f \left( \frac{18,400 \text{ Btu/lb}}{\text{Actual LHV}} \right)$$

Metric conversions: kPa = 6.894 757 psia  
 °C = (°F-32)/1.8  
 kg = 0.453 592 lbm  
 MJ/kg = 0.002 326 Btu/lb

TABLE 6-3. TEST CYCLE FOR 1,000 HOUR ENDURANCE TEST<sup>(6-1)</sup>

Time (min)	Turbine inlet temp (°F)	Nominal load, kW
5	1180	300
30	1325	750
25	1475	1250
60	1870	2500 (100%)
30	1780	2250
30	1725	2000
30	1870	2500 (100%)
30	1180	300
30	1870	2500
30	1780	2500
30	1870	2250
60	1245	500
30	1475	1250

- Notes: 1. Controlled to turbine temperature, accepted resulting electrical load.  
 2. Above schedule repeated three times, then followed by 3 hr of downtime during which three starts were made.  
 3. During each 7-hr cycle, the compressor discharge (14th-stage) air was bled for 30 min duration while the engine was operating at 1870°F turbine inlet temperature. The bleed airflow was a nominal 2.37 lb/sec.  
 4. Compressor inlet temperature was controlled to 100°F.  
 5. Metric conversions: °C = (°F-32)/1.8  
 kg/s = 0.453 592 lbm/sec



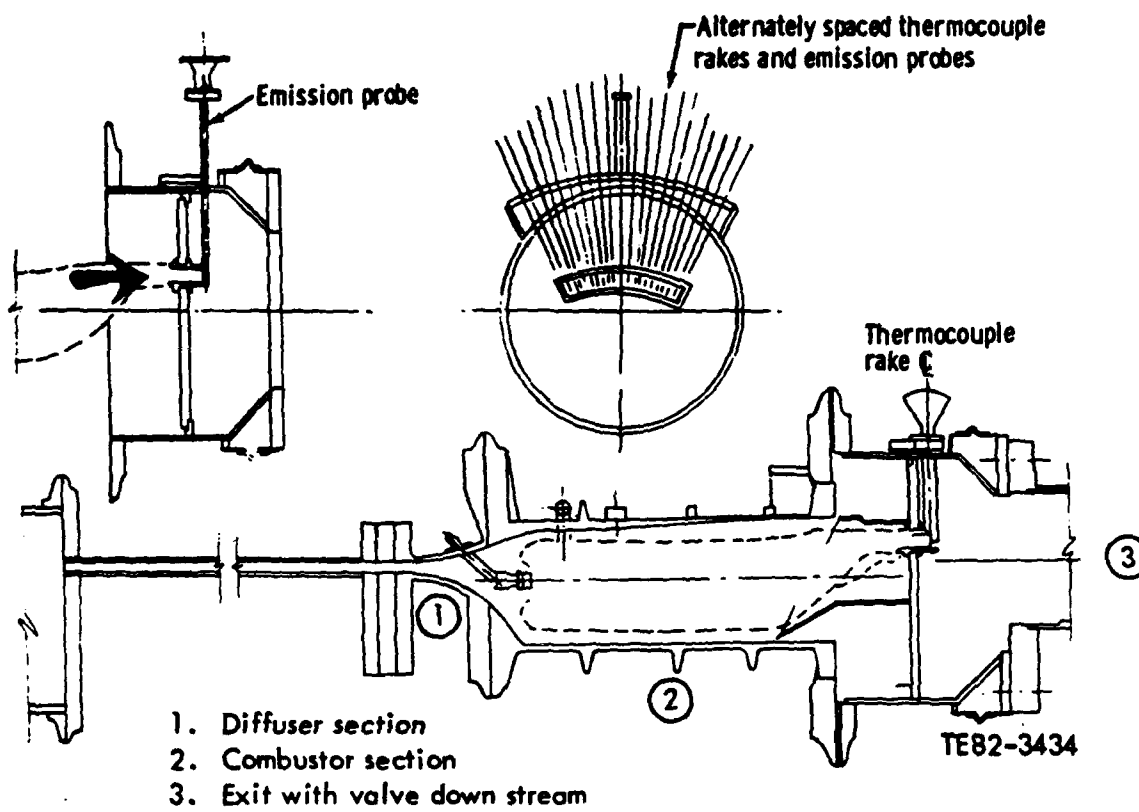
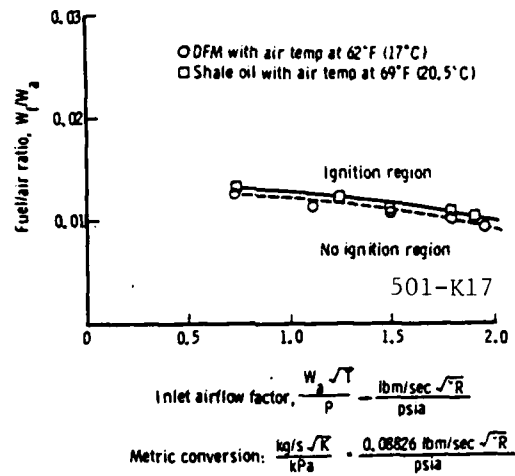
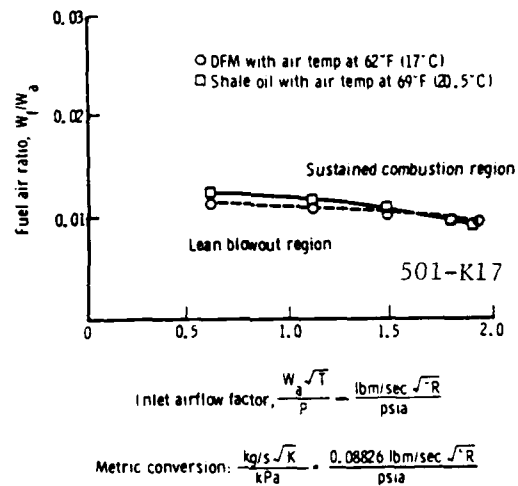


FIGURE 6-1. SINGLE-BURNER TEST RIG<sup>(6-1)</sup>  
FOR DDA 501-K17 BURNER

FIGURE 6-2. IGNITION CHARACTERISTICS, BURNER TEST RIG<sup>(6-1)</sup>FIGURE 6-3. LEAN BLOWOUT LIMITS, BURNER TEST RIG<sup>(6-1)</sup>

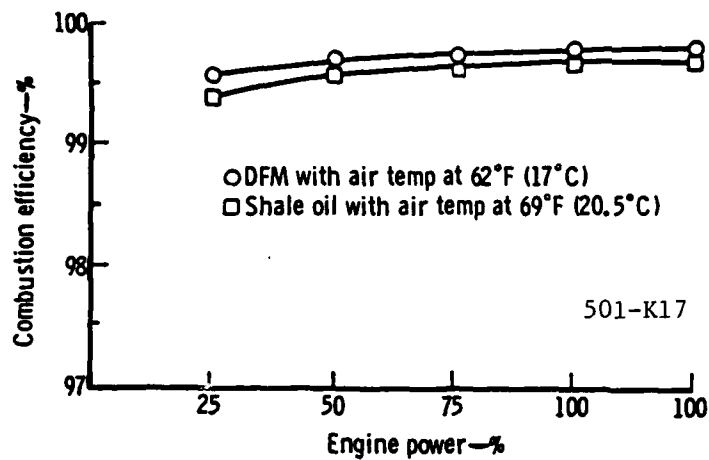


FIGURE 6-4. CALCULATED COMBUSTION EFFICIENCY,  
BURNER RIG TESTS (6-1)

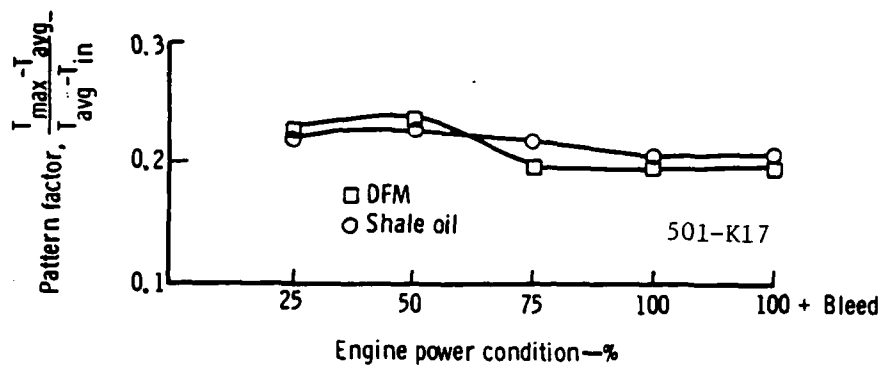


FIGURE 6-5. COMBUSTOR OUTLET TEMPERATURE PATTERN FACTORS,  
BURNER RIG TESTS (6-1)

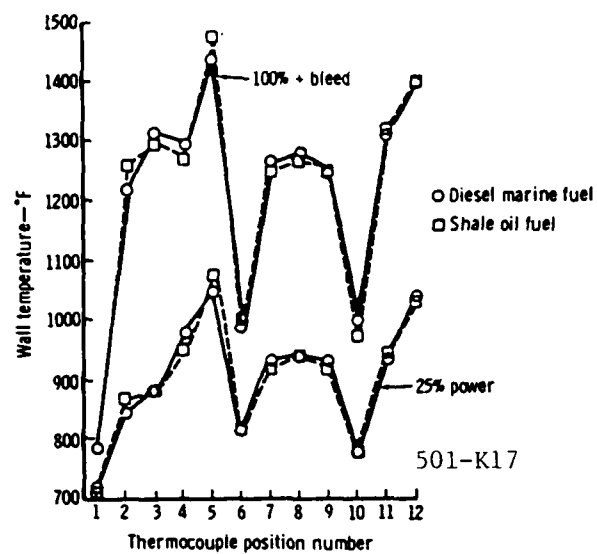


FIGURE 6-6. COMBUSTOR WALL TEMPERATURES,  
BURNER RIG TESTS (6-1)

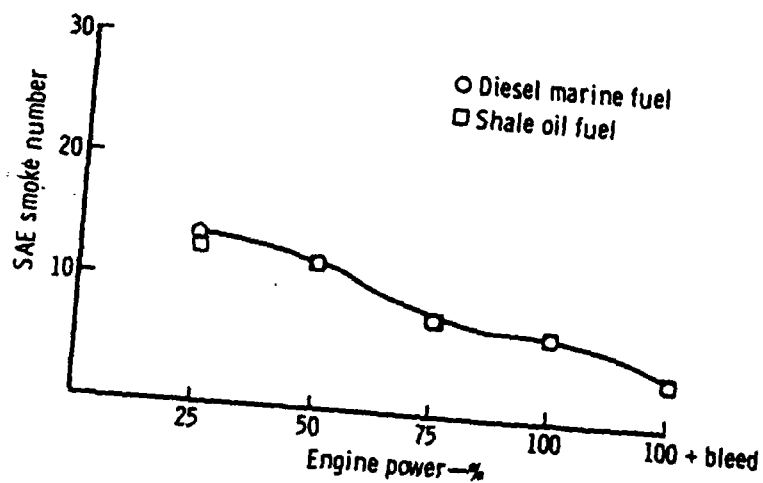


FIGURE 6-7. SMOKE VALUES FOR COMBUSTOR RIG TESTS (6-1)

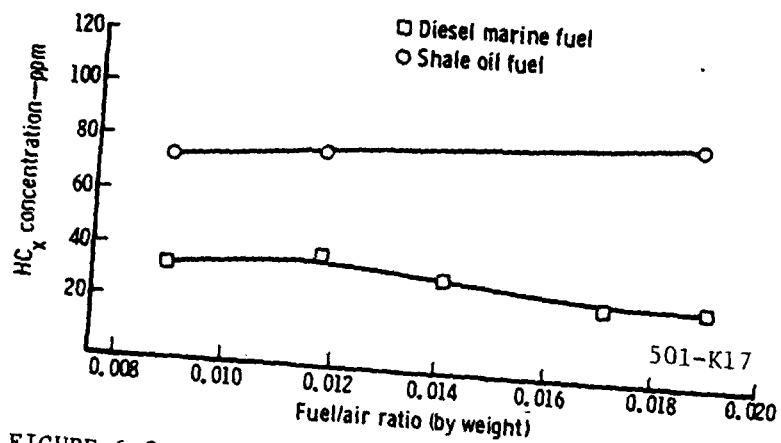


FIGURE 6-8. HYDROCARBON EMISSIONS, COMBUSTOR RIG TESTS (6-1)

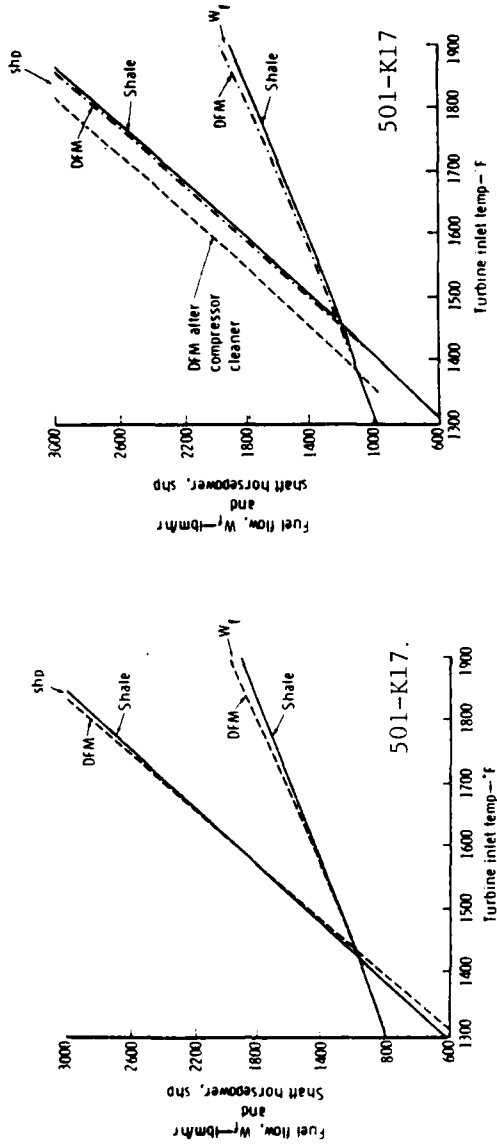


FIGURE 6-9. PRE-ENDURANCE PERFORMANCE(6-1) FIGURE 6-10. POST-ENDURANCE PERFORMANCE(6-1)

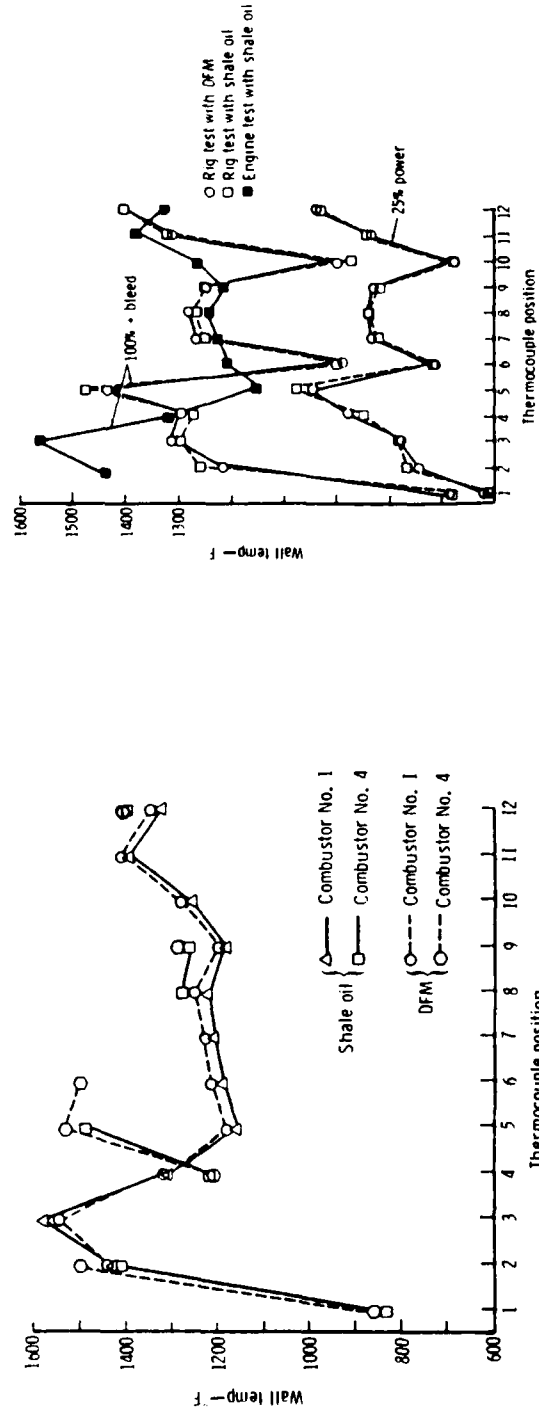


FIGURE 6-11. COMBUSTOR WALL TEMPERATURES, (6-1)  
100 PERCENT POWER PLUS BLEED

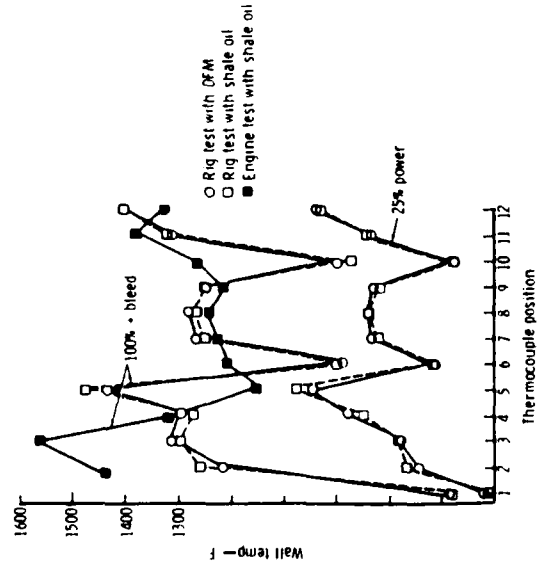


FIGURE 6-12. COMBUSTOR WALL TEMPERATURES  
COMPARISON, RIG TO ENGINE(6-1)

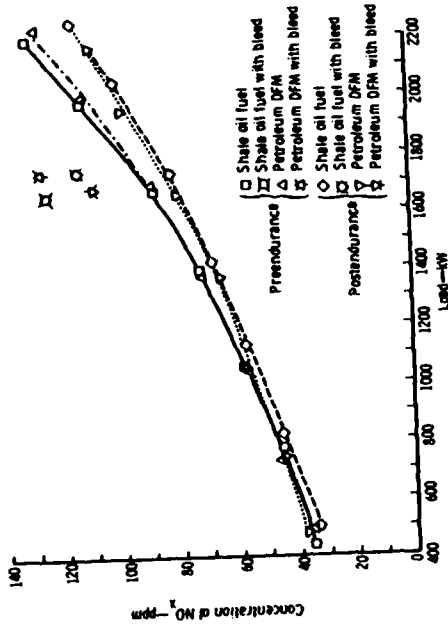
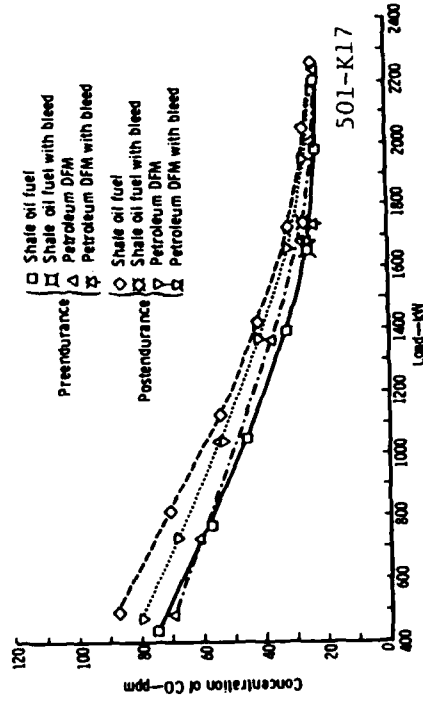
FIGURE 6-15. ENGINE TEST NO<sub>x</sub> EMISSIONS (6-1)

FIGURE 6-16. ENGINE TEST CO EMISSIONS (6-1)

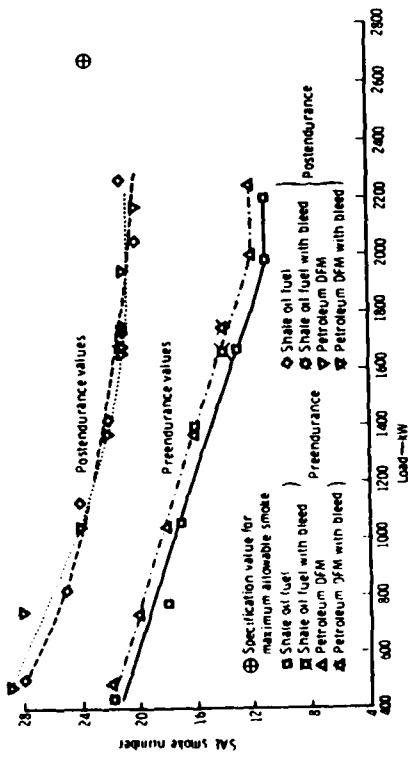
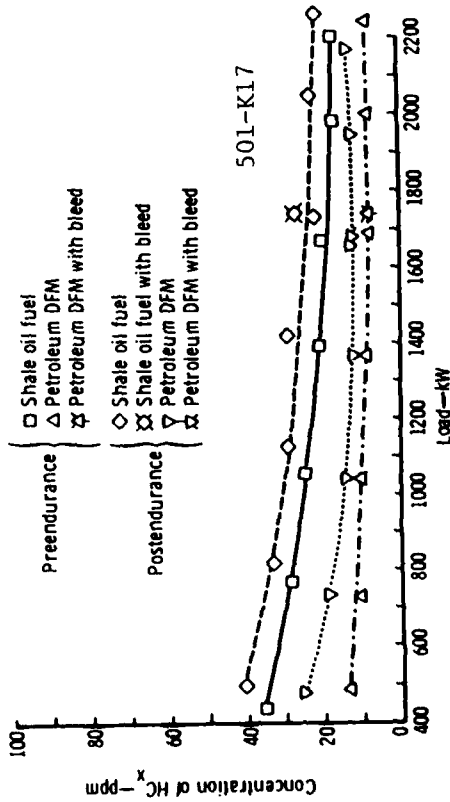


FIGURE 6-13. ENGINE TEST SMOKE VALUES (6-1)

FIGURE 6-14. ENGINE TEST HC<sub>x</sub> EMISSIONS (6-1)

## 7. GENERAL ELECTRIC TESTS OF LM-2500 GAS TURBINE (References 7-1, 7-2)

### Summary

Tests of the LM2500 engine were carried out by the General Electric Company at their Evendale facilities to evaluate the effects of shale DFM on performance, emissions, and endurance of the LM2500 engine. The LM2500 engine is used as the main propulsion engine in the DD963 (Spruance), the DDG993 (Kidd), and CG47 (Ticonderoga) classes of ships.

Back-to-back tests with DFM and shale DFM were carried out in a combustor rig at atmospheric pressure. Pattern factor, temperature profiles, lightoff characteristics, lean-blowout characteristics, and low-power efficiencies were determined for both fuels with almost identical results.

Following the combustor rig tests, back-to-back engine tests were run throughout the power range of the engine. Data included engine thermodynamic and mechanical performance, outer combustor liner temperatures, exhaust emissions, and smoke. Test results for the two fuels were identical. The only observed difference was that the shale DFM consistently showed a higher smoke number for equivalent power settings, although the smoke number was well below specification for both fuels. Post-test examination showed no adverse effects of the shale DFM.

It was concluded that the shale DFM used for these tests was a premium fuel that was unequivocally acceptable as an alternative to petroleum DFM. The fuel quality could have been significantly lower without adversely affecting the engine.

### Detailed Analysis of Shale DFM

Before engine tests were considered, a sample of shale DFM was analyzed in detail to determine its suitability for gas turbine use.

Table 7-1 lists properties of the shale DFM as determined by the General Electric analysis. On the basis of this analysis, the shale DFM was judged to be an excellent fuel for gas turbines and the LM2500 tests were recommended.

### Engine Description

The General Electric LM2500 engine is a 21,500 hp ship propulsion turbine derived from the TF39/CF6-6 aircraft turbofan engine. The 16-stage compressor incorporates 7 stages of variable stator vanes, for a pressure ratio of 18. A 2-stage, air-cooled turbine drives the compressor, and a 6-stage free turbine drives the load at 3600 rpm. The



annular combustor has 30 duplex fuel nozzles and, at full power, operates with inlet air temperature of 1000 F and exit gas temperature of 2350 F.

### Combustor Rig Tests

#### Combustor Test Conditions

Combustor rig tests were run using a full annular combustor operated at atmospheric pressure. Combustion air was heated to inlet temperatures up to 1000 F in a heat exchanger at approximately 7.44 lb/sec, and full load combustor exit temperature was 2350 F. A standard LM2500 performance test was conducted to determine exit temperature profile and pattern factor, first on DFM, then on shale DFM. For these atmospheric-pressure tests, standard component-test simplex fuel nozzles were used with flow characteristics matched to airflows at atmospheric pressure. For tests of ground-starting ignition and low-speed efficiency tests, 30 standard LM2500 dual-orifice nozzles were installed.

Figure 7-1 is a section of the LM2500 combustor.

#### Radial Profile and Pattern Factor

Figure 7-2 shows a comparison of radial profile and pattern factor for DFM and shale DFM fuels. The radial profile is virtually identical for these two fuels, although the pattern factor plots show slightly higher temperature with shale DFM (+21 to 60 F) at all immersions except the root and tip immersions, where shale DFM shows lower temperature (-33 to -7 F). The overall pattern factor was 0.232 for DFM and 0.230 for shale DFM. In carrying out these tests, four 7-element thermocouple rakes were rotated around the combustor exit plane at increments of 1.5 degrees and the values for each radial location averaged. In each 90-degree sector, temperatures were measured at 420 points, for a total of 1680 points.

Starting and ignition characteristics of the combustor were determined at combustor airflows of 6, 8, and 12 lb/sec, and the fuel rate needed for ignition and full flame propagation was determined at each airflow rate with both DFM and shale DFM.

Figure 7-3 compares full propagation ignition characteristics of DFM and shale DFM. The fuel flow required for full propagation at an airflow of 8 lb/sec is usually quoted as the fuel required to start the engine. Based on this definition, the amount of fuel required to start the engine is 455 lb/hr for both DFM and shale DFM. At airflow rates greater than 9 lb/sec the two curves in Figure 7-3 diverge, and the fuel flow rate for shale DFM is about 22 percent lower than that for DFM.

The lower fuel flow required for full flame propagation with shale DFM does not seem to have any additional significance because test experience indicates that the airflow required to start the LM2500 engine is between 8 and 10 lb/sec, and the test data in Figure 7-3 show nearly the same fuel flows for both fuels in this airflow range.

#### Low-Speed Efficiency

Figure 7-4 represents low speed combustion efficiency plotted as temperature rise versus fuel/air ratio. The actual combustor temperature rise is calculated using the corrected average combustor exit gas temperature, corrected for thermocouple radiation error, and the inlet temperature. The curves for combustion efficiency are based on JP-5 fuel having a lower heating value of 18,550 Btu/lb, compared with 18,328 Btu/lb for DFM and 18,486 for shale DFM. This difference introduces an error of only 1 percent.

In Figure 7-4, the temperature rise for shale DFM is consistently higher than that for DFM. At airflow of 8 lb/sec this difference is 50 F, but at 6 lb/sec it is only 20 F. Past results of testing of other production LM2500 combustors have shown a similar range of temperature differences from test to test for the same combustor and fuel. Based on this experience it appears possible that the difference in temperature rise for DFM and shale DFM is within the experimental repeatability of test data. The difference is not considered to be very substantial, and General Electric anticipates no problems in operating an engine on shale DFM.

#### Engine Tests

##### Test Schedule

The engine used for shale DFM evaluation was Engine 446-807/11, an LM2500 gas generator without power turbine. This engine was made available by NAVSEA from the LM2500 Component Improvement Program. The test was completed November 19, 1979 and included 20.5 hours of operation.

Table 7-2 shows the specific test points at which data were taken. Tests were run at corrected speeds starting at idle (5000 rpm), increasing in increments until maximum destroyer application power (21,500 SHP) was reached. Data measured included test performance, exhaust emissions, smoke level, and combustor outer liner temperatures. These were taken in back-to-back tests burning DFM and shale DFM.

### Performance Tests

Before starting performance tests the engine was cleaned using a standard wash procedure (B&B 3100 solvent and water injected into the compressor inlet) to eliminate possible flow-path fouling. Data were taken at corrected speeds shown in Table 7-2, starting at idle and progressing to full load. Load was stabilized for 5 minutes at each point, after which two sets of data were taken using an automatic data handling system. The initial test was conducted using DFM, followed by the shale DFM test and a repeat of the DFM test. Fuel samples were obtained before and after these tests.

Performance for the two fuels was normalized for fuel heating value. Four bomb calorimeter tests were performed for each fuel, and the lower heating value of the shale DFM was determined to be 18,479 Btu/lb with agreement within 0.06 percent among the four determinations. The lower heating value of the DFM was measured at 18,328 Btu/lb.

Table 7-3 shows the results of abbreviated fuel analyses run before and after engine tests. Fuel properties for both DFM and shale DFM are seen to be very consistent, and the differences between the fuels are small.

Results of performance tests indicate that engine performance with shale DFM is identical to that for DFM when normalized for the difference in heating values. Results show that:

1. The combustibility of the two fuels is identical.
2. Pressure loss due to combustion is the same for both fuels.
3. The thermodynamic properties of the products of combustion are the same for both fuels.
4. The measured fuel flow rates for both fuels were consistent and accurate.

Figures 7-5 and 7-6 compare exhaust temperatures and heat rates for the two fuels at constant isentropic gas horsepower. The data show no identifiable difference between the two fuels, demonstrating that both fuels exhibit the same exhaust gas properties.

### Exhaust Emissions

Engine exhaust emissions were measured using standard techniques. The engine exhaust was sampled by two probes which withdrew samples at selected points as shown in Figure 7-7. The sampling probes were steam cooled and the sample lines were steam traced or electrically heated to avoid condensation. Four Beckman gas analyzers were used: Model 865 NDIR for CO, Model 864 NDIR for CO<sub>2</sub>, Model 951

chemiluminescence analyzer for  $\text{NO}_x$ , and a Model 402 flame ionization detector for HC. Water traps were used before the NDIR analyzers, but no traps were used before the HC and  $\text{NO}_x$  analyzers, which are not sensitive to water. All instruments were calibrated before and after each test.

Smoke number was measured by a reflectance measurement from a stain left by passing a measured quantity of exhaust gas through a filter, following SAE ARP 1256. All emission data were manually logged, then fed into a computer data reduction program for calculation of emission index, combustion efficiency, and fuel/air ratio.

Figures 7-8, 7-9, and 7-10 present emission data for CO, HC, and  $\text{NO}_x$  in terms of emission index, defined as lb emitted/1000 lb fuel. Figure 7-11 presents smoke data in terms of SAE smoke number.

The CO emission index, Figure 7-8, is identical for DFM and shale DFM at all test points except one, where the value for shale DFM is slightly higher. The difference does not appear significant.

The HC emission index is the same for both fuels at the three highest test temperatures (highest loads), but the values for shale DFM are higher than those for DFM at the lower exhaust temperatures representing light loads.

The  $\text{NO}_x$  emission index, Figure 7-10, is slightly lower for shale DFM than for DFM at all test conditions.

In Figure 7-11, smoke number is plotted against IGP (indicated gas horsepower). The smoke numbers for all test points were below the LM2500 specified value of 20, the highest value being about 10. The shale DFM shows slightly higher smoke values than DFM at the two high-load points, but the values shown are only half the specified limits. Past experience indicates that variability of measurements in the 0-10 range is much greater than that at higher levels of smoke number.

#### Combustor Liner Temperatures

Thermocouples were installed on six of the outer panels to measure temperatures at 7 locations on each panel, for a total of 42 thermocouples. Measurements were made on Panels 2, 3, 4, 7, 8, and 9, covering the entire length of the combustor liner. Data were reported in terms of  $(T_{\text{liner}} - T_{\text{air in}})$ , and plotted against theoretical combustor temperature rise. The measured temperatures for DFM and shale DFM proved identical for all panels except Panel 2, for which the temperature rise for shale DFM was 20-30 F lower than for DFM.

Figure 7-12 shows metal temperature data for Panel 2 of the combustor/outer liner.

### Engine Inspection

Borescope inspections were performed on the hot section before and after the shale DFM test on the engine. No changes were apparent in the condition of the combustor or high pressure turbine. Inspections were made through the compressor rear frame borescope ports at the 3, 6, and 9 o'clock locations. Probe scans were made looking forward to the combustor, aft towards the turbine, and in both circumferential directions. Additional inspections were made through the HPT borescope port locations. Following this special fuel test the engine went directly to the planned LM2500 CIP Program 100 hour endurance test, which was conducted using JP-5 fuel. Subsequent inspection of the hardware after disassembly did not reveal any unusual part condition.

### Conclusions

It was concluded that the shale DFM used for these tests was a premium fuel that was unequivocally acceptable as an alternative to petroleum DFM. The fuel quality could have been significantly lower without adversely affecting the engine.

### References

- 7-1. "Evaluation of Diesel Fuel Marine Derived From Shale Oil", prepared under Contract N61533-79-M-2235 for Naval Ship R&D Center by General Electric Company, Cincinnati, Ohio, Document No. NSRDC-01, July 17, 1979.
- 7-2. "Shale Derived Fuel Oil Engine Suitability Investigation LM2500 Shale Fuel Oil Test Program" prepared under Contract F34601-G-79-0212 SB09 for Naval Ship R&D Center by General Electric Company, Cincinnati, Ohio, Document No. NSRDC-02, January 22, 1980.

TABLE 7-1. PROPERTIES OF SHALE DFM(7-2)

PROPERTY		MIL-F-16886 REQUIREMENT		MIL-F-16884 REQUIREMENT	
Shale DFM		Shale DFM		Shale DFM	
Catane Index		55		NR	
Appearance		Clear, bright, and free from visible particulate matter		NR	
90% Distillation Point		563°F		NR	
End Point		580°F		NR	
Residue Plus Loss		2.3%		NR	
Flash Point		166°F		NR	
Pour Point		-20°F		NR	
Cloud Point		0°F		NR	
Viscosity at 100°F		2.72 cs		NR	
Carbon Residue on 10% Bottoms		0.078%		NR	
Sulfur		3 ppm (0.0003%)		NR	
Copper Strip Corrosion at 212°F		No. 2		NR	
Ash		0.0003%		NR	
Specific Gravity at 60°F		0.8337		NR	
Demulsification		39-36-5 after 60 Minutes		NR	
Acid Number		0.007		NR	
Water and Sediment		<0.003%		NR	
Total Water Content		18 ppm		NR	
Particulate Matter (> 0.8 μ)		4.92 mg/gal.		NR	
Lower Heating Value		18,476 Btu/lb.		NR	
Hydrogen Content		13.43%		NR	
Smoke Point		17.0		NR	
Compatibility with JP-5 and Marine Diesel		Compatible		NR	
NOTES:		NR = No Requirement		(7) Requirement for JP5 is 13.5% min.; for MAI fuel, it is 12.5% min.	
(1) Standard 1 indicates slight tarnish; Standard 2 indicates moderate tarnish. Corrosion is indicated by a Standard of 4. Jet A fuel has been accepted as a "2".		(2) Limits for JP5 are 0.788 to 0.845.		(8) Alternative requirement for JP5 is 19.0 min.	
(3) 40 cc's of oil and 40 cc's of 1% sodium chloride and water are mixed. A trace of emulsion was present in the shale oil after 60 minutes.		(4) Water in test above is free water only.		(9) Requirements for MAI fuel spec. are 0.5 and 1.0 ppm max., without and with marine coatings, respectively.	
(5) Requirement for JP5 is 3.79 mg/gal. max.		(6) Requirement for JP5 is 18,300 Btu/lb. min.		(10) Sodium plus potassium requirements for MAI fuel spec. are 0.5 and 1.0 ppm max., without and with marine coatings, respectively.	
(16) Requirement for JP5 is 18,300 Btu/lb. min.				(11) Requirements for MAI fuel spec. are 1.0 and 2.0 ppm max., without and with marine coatings, respectively.	
				(12) Requirement for MAI fuel spec. is 0.5 ppm max.	
				(13) No requirement in any specification. Navy considers any value below 0.43 is good. (Reference NAC Report No. NACPC-PE-112, "Lubricity Properties of High Temperature Jet Fuel", August, 1977.)	
				(14) Elastomer Spec. requires 1 to 25%.	
				(15) Elastomer Spec. requires 1 to 10%. (The change in volume is not considered significant to CAA designers who consider initial compression set significant to "O" ring sealing.)	

TABLE 7-2. LM-2500 ENGINE TEST POINTS<sup>(7-2)</sup>

<u>Corrected Speed-RPM</u>	<u>Performance</u>	<u>Emissions</u>	<u>Smoke</u>	<u>Comb. Liner Temp</u>
5000 (Idle)	X	X	X	X
5500	X	X	X	X
6000	X	X	X	X
6500	X			X
7000	X	X	X	X
7250	X			X
7500	X	X	X	X
7750	X			X
8000	X	X	X	X
8250	X			X
8500	X	X	X	X
8750	X	X	X	X

TABLE 7-3. RESULTS OF ENGINE TEST FUEL ANALYSES<sup>(7-2)</sup>

	Shale DFM				Petroleum DFM	
	<u>Before Test</u>		<u>After Test</u>		<u>Before Test</u>	
	<u>Upstream Of Filter</u>	<u>Downstream Of Filter</u>	<u>Upstream Of Filter</u>	<u>Downstream Of Filter</u>	<u>Upstream Of Filter</u>	<u>Downstream Of Filter</u>
Viscosity at 100°F-CS	2.71	2.71	2.72	2.72	2.74	2.74
Specific Gravity at 60°F	.8337	.8334	.8338	.8339	.8471	.8474
Hydrogen Content - %	13.43	13.43	13.47	13.47	13.07	13.04
Sulfur Content - %	0.01	0.01	.014	.014	0.15	0.15
Lower Heating Value-BTU/#	18,485	18,485	18,475	18,464	18,310	18,314
Flash Point - °F	170	162	172	168	142	140
Water Content-PPM	40	39	41	41	52	47
Particulate Matter-Mg/Gal.	6.43	5.30	5.68	5.30	32.55	22.71
Ash - %	.003	.002	.003	.001	-	-
Carbon Residue - 10% Bottoms	.10	.11	.10	.11	-	-
Appearance	Clear/ Water White $\longrightarrow$				Clear/ Amber $\longrightarrow$	

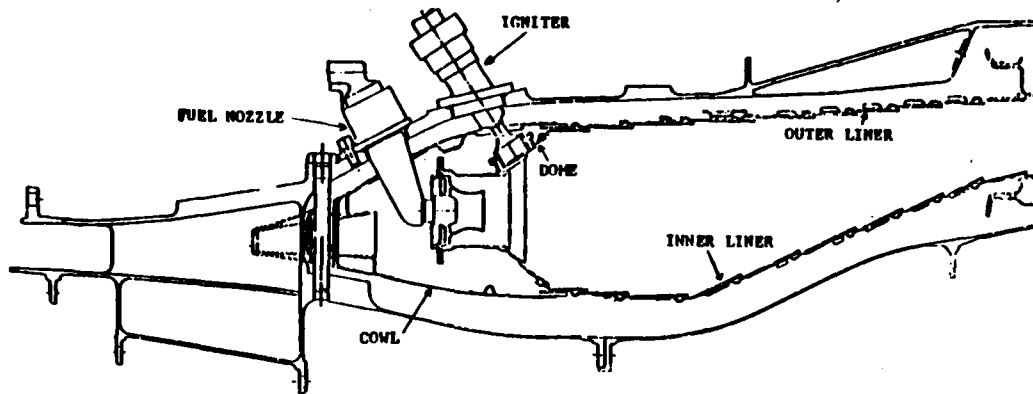


FIGURE 7-1. LONGITUDINAL SECTION OF LM2500 ANNULAR COMBUSTOR<sup>(7-2)</sup>

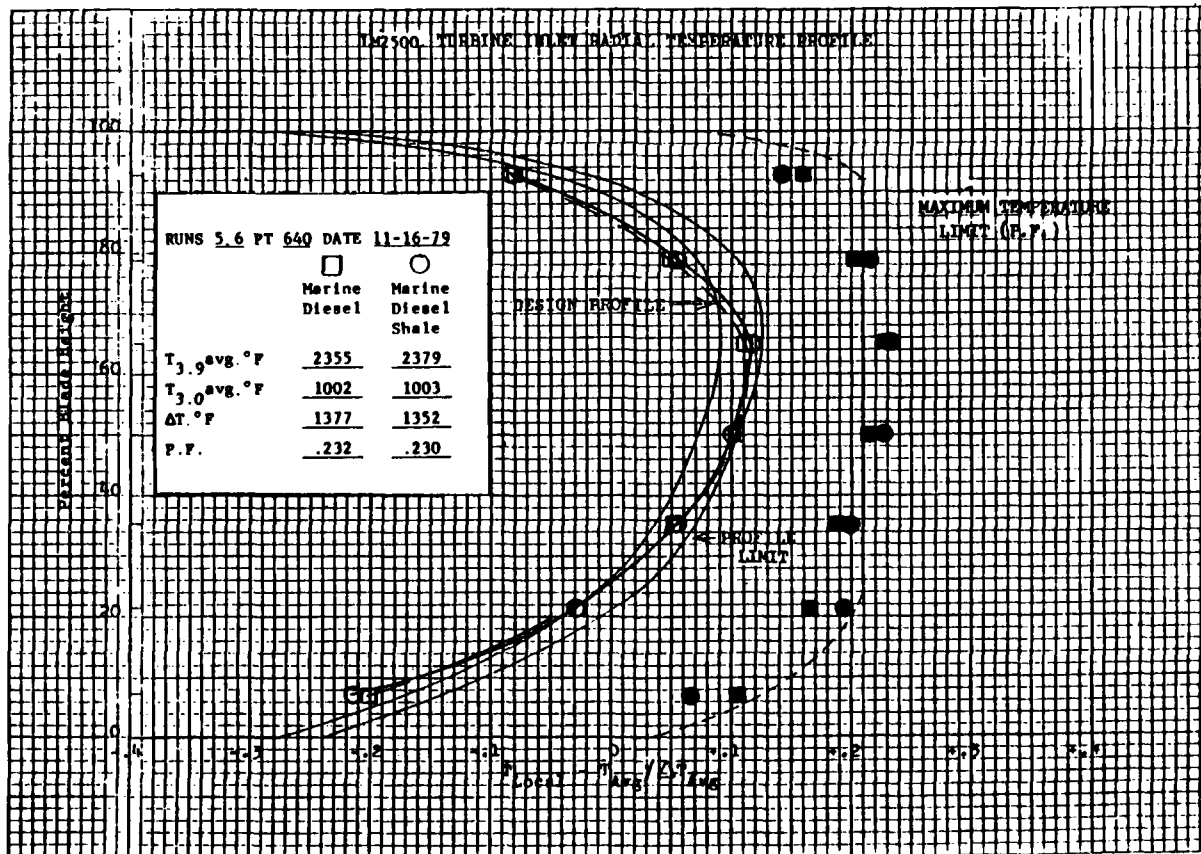
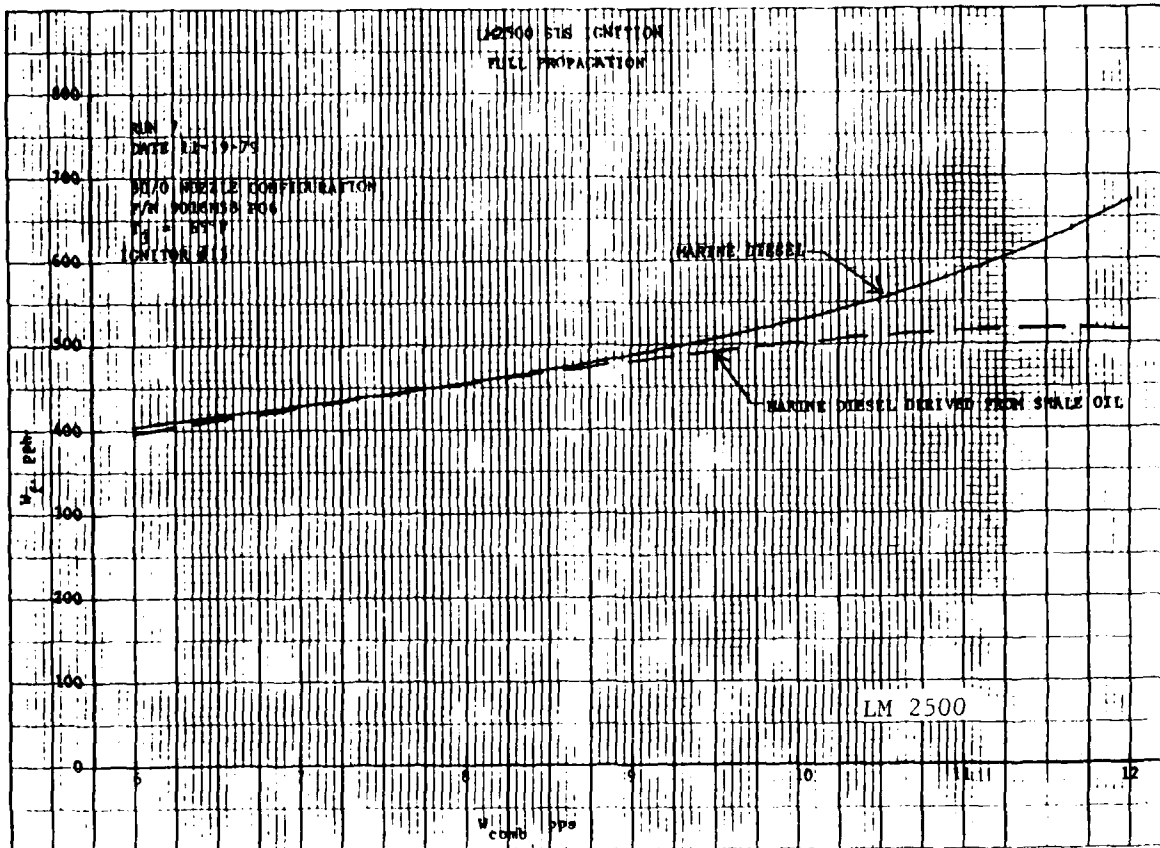
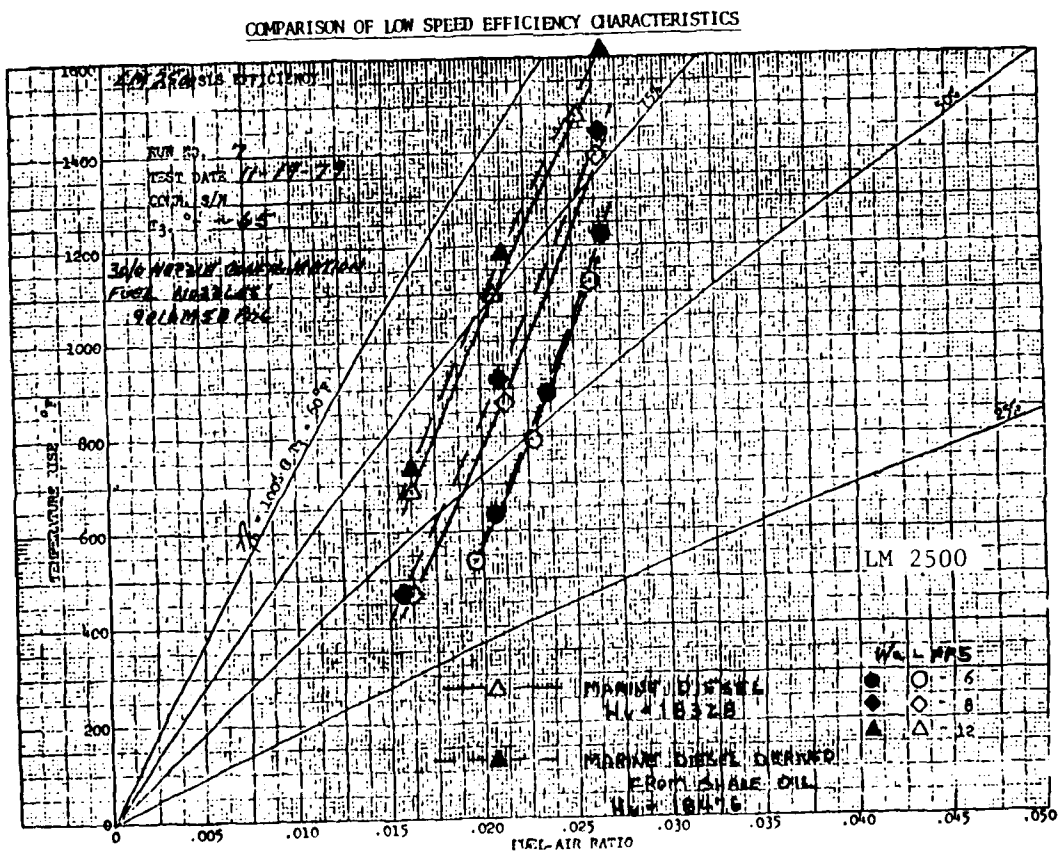


FIGURE 7-2. LM2500 TURBINE INLET RADIAL TEMPERATURE PROFILE<sup>(7-2)</sup>



FIGURE 7-3. LM2500 SLS IGNITION/FULL PROPAGATION<sup>(7-2)</sup>FIGURE 7-4. COMPARISON OF LOW SPEED EFFICIENCY CHARACTERISTICS<sup>(7-2)</sup>

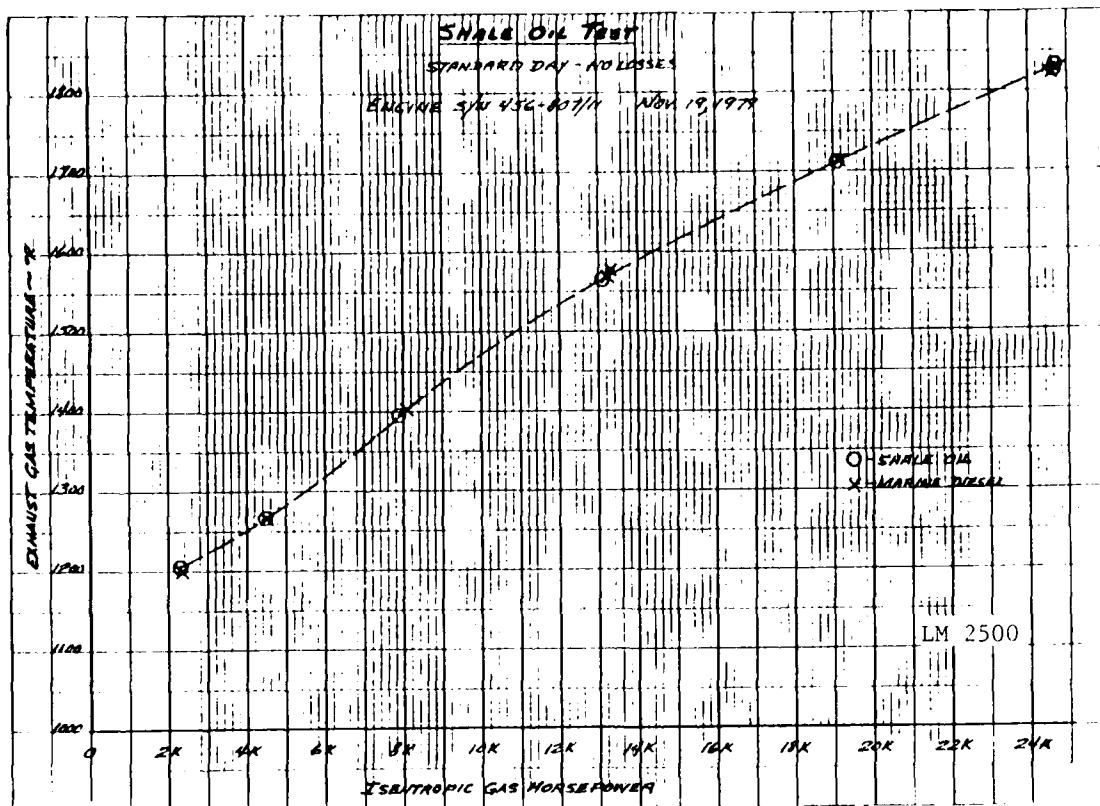


FIGURE 7-5. EXHAUST GAS TEMPERATURE (7-2)

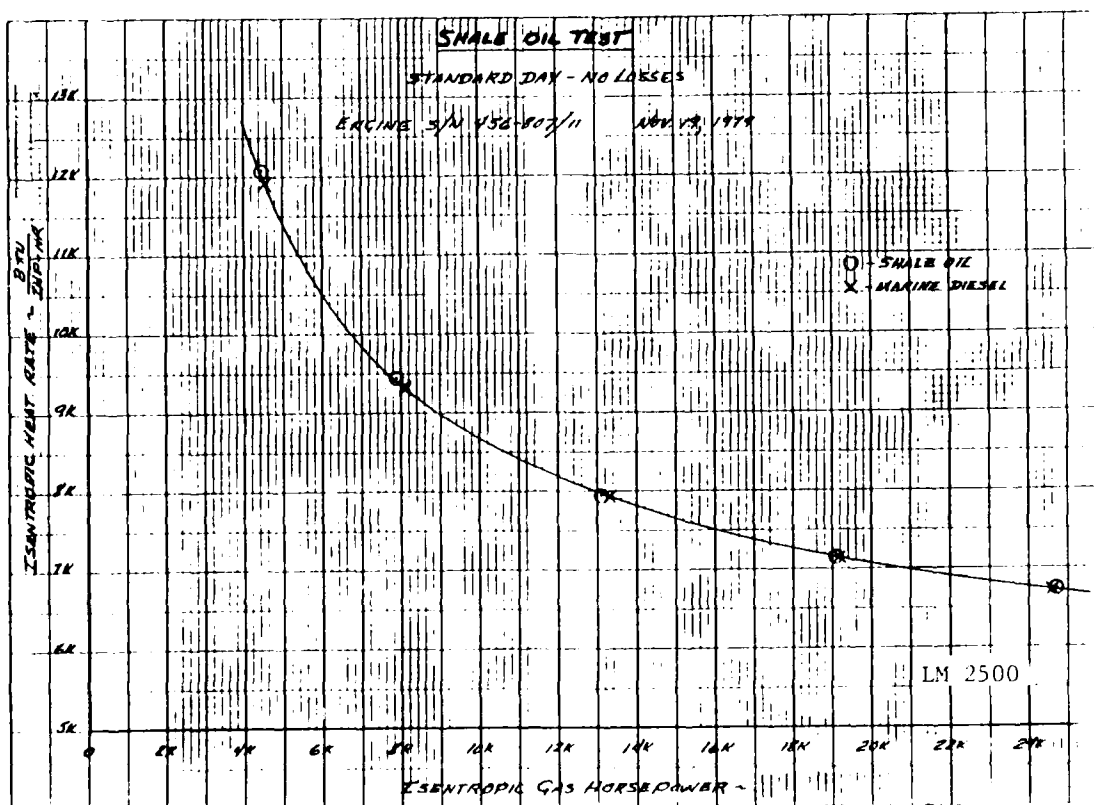


FIGURE 7-6. ENGINE HEAT RATE (7-2)

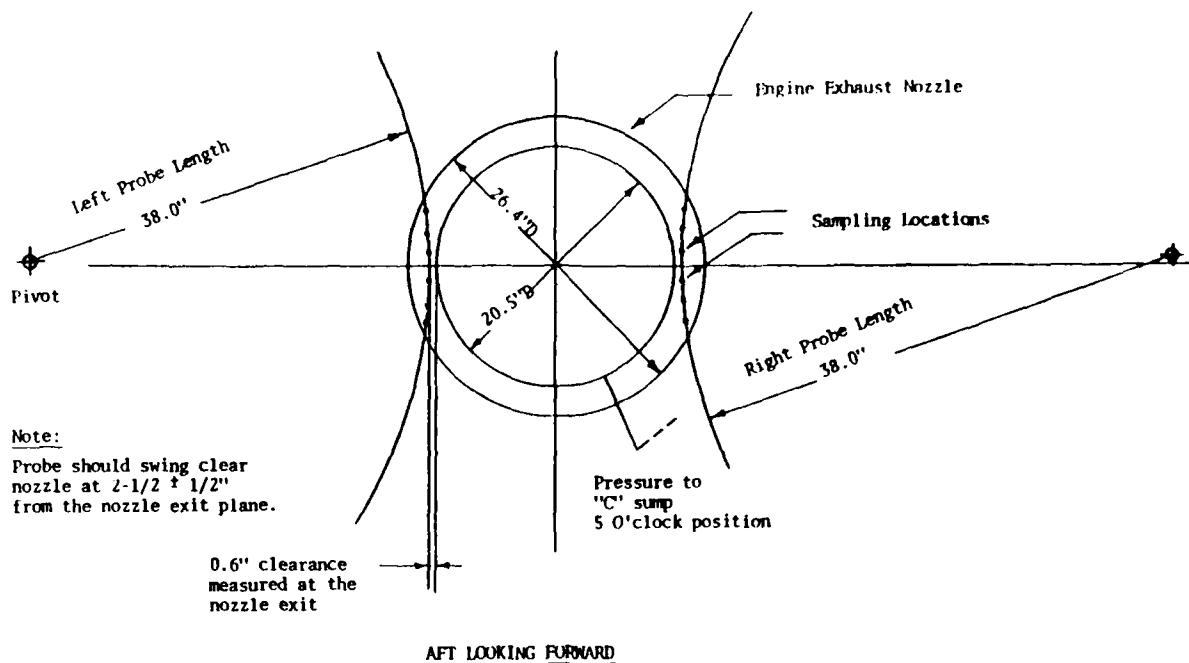


FIGURE 7-7. SCHEMATIC OF EMISSIONS SAMPLING PROBE SETUP(7-2)

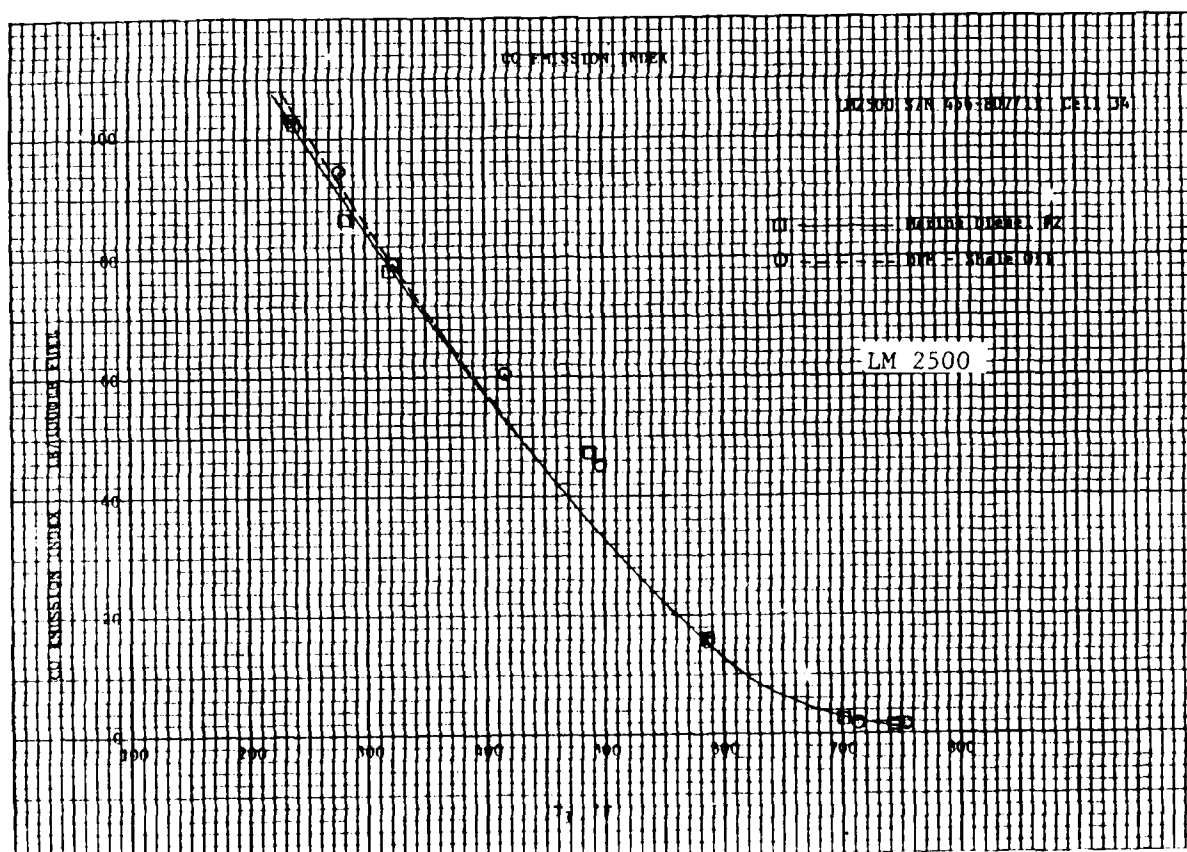
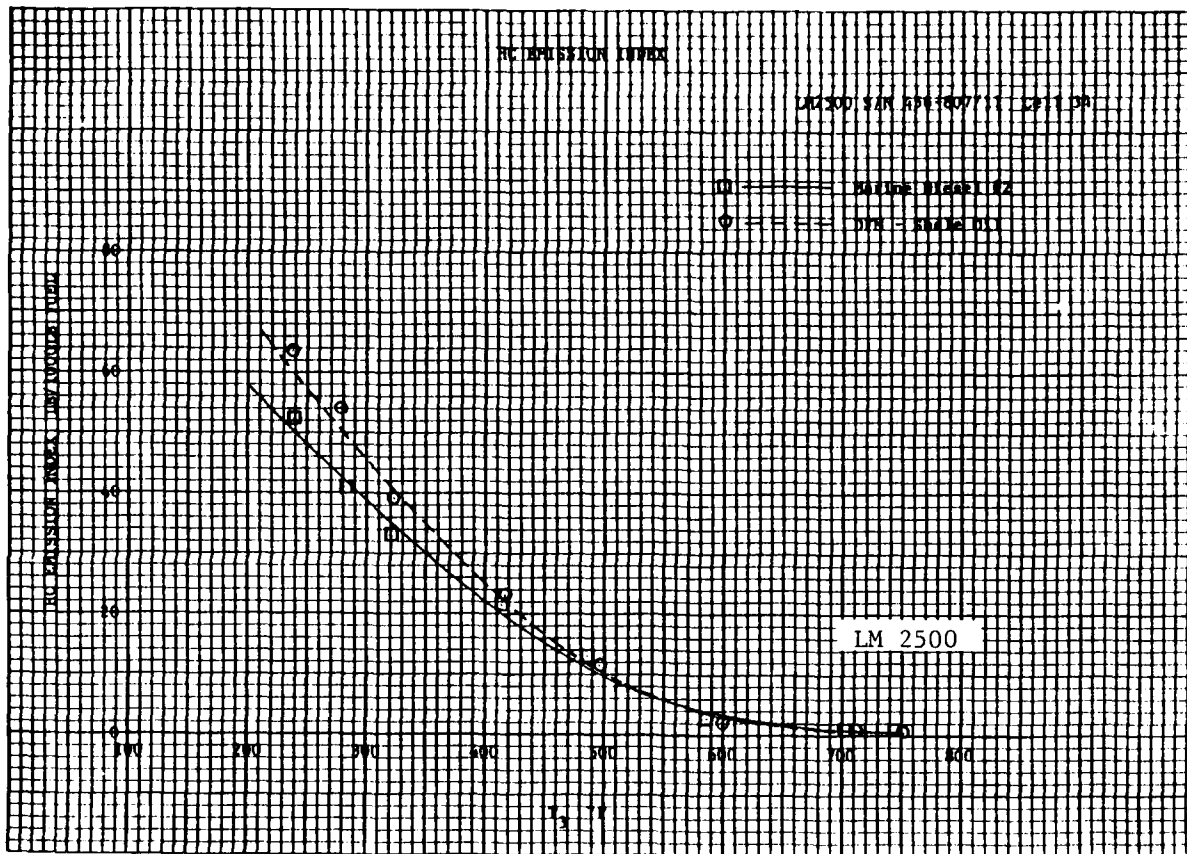
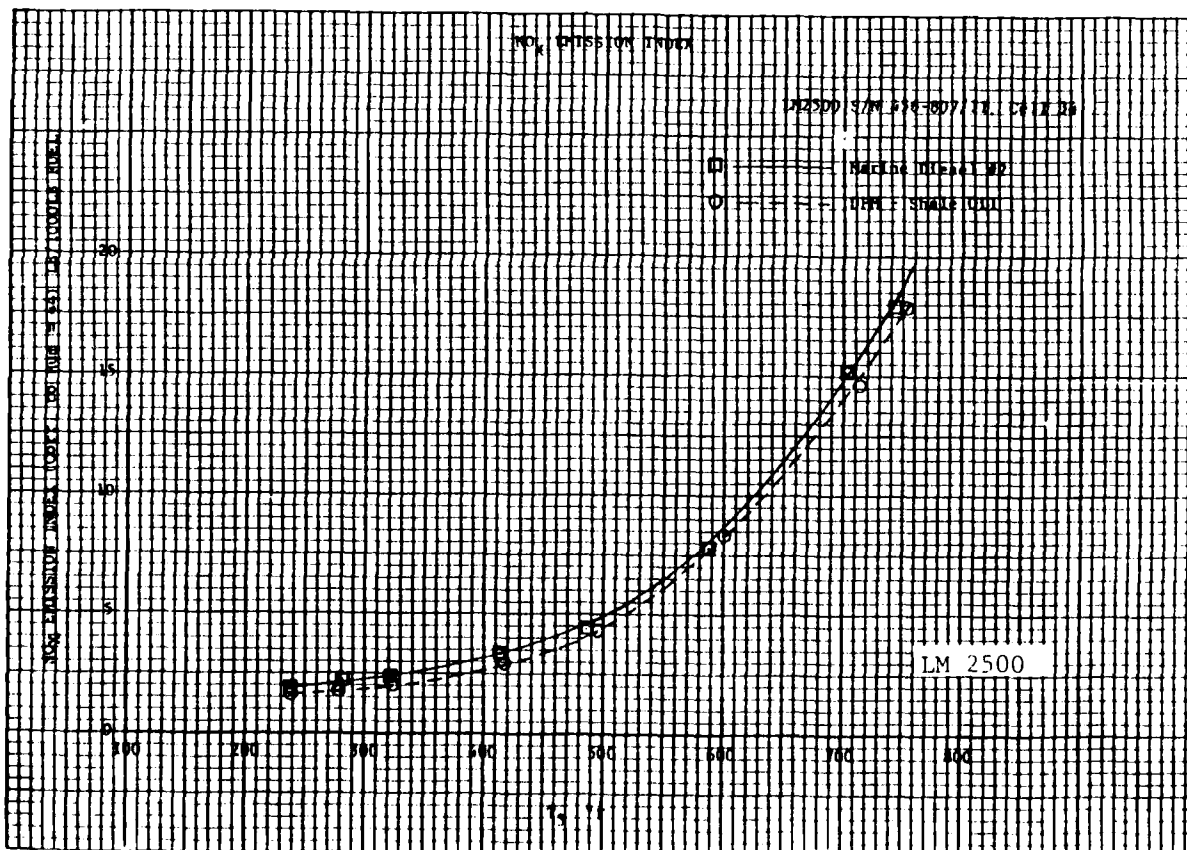
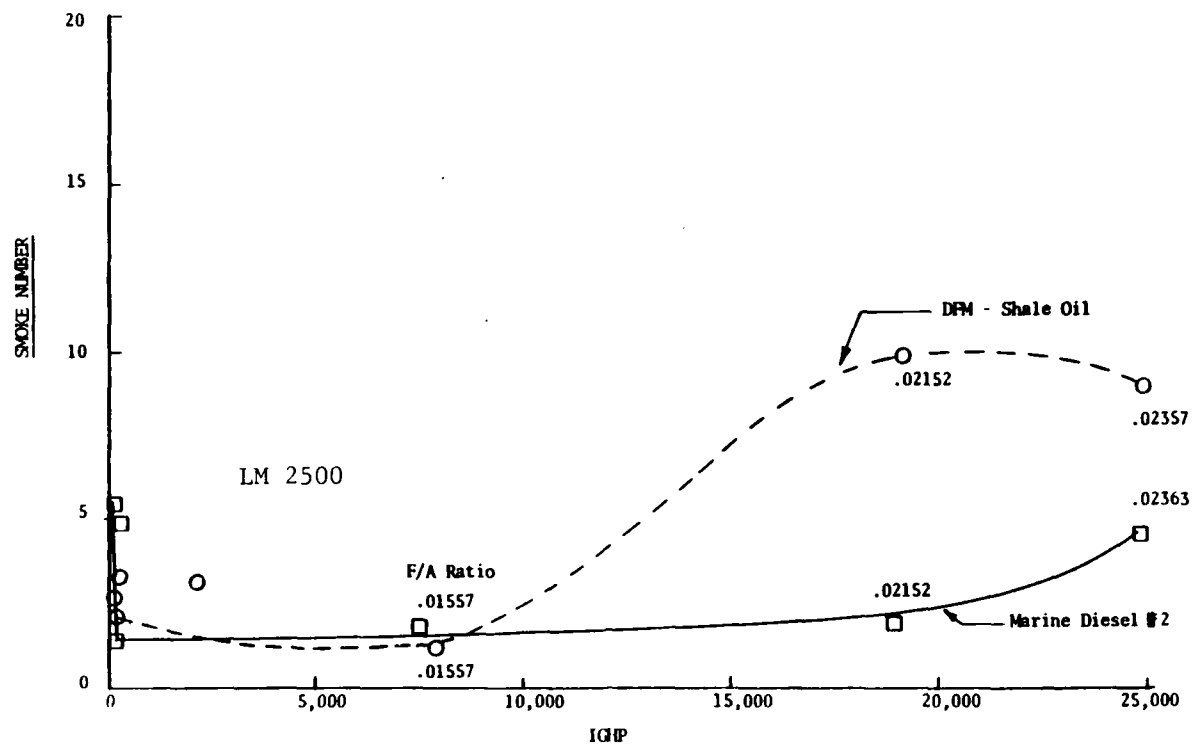
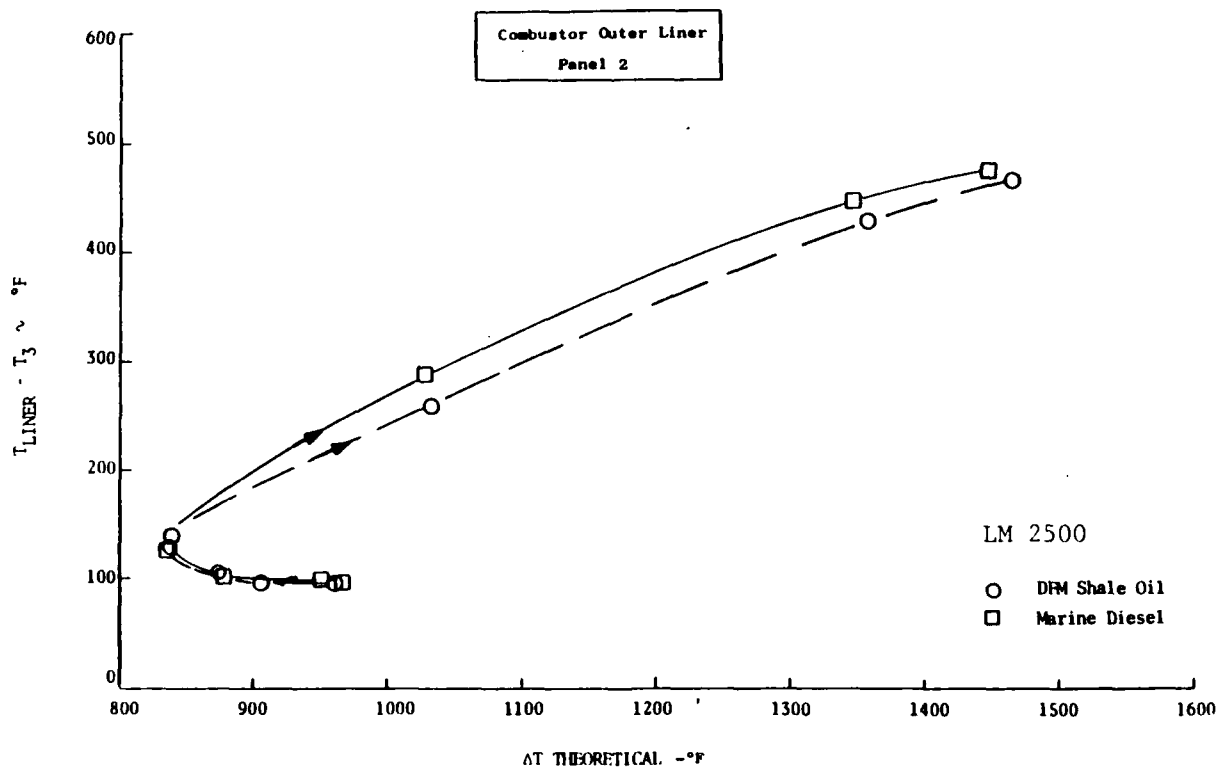


FIGURE 7-8. CARBON MONOXIDE EMISSIONS<sup>(7-2)</sup>

FIGURE 9. HYDROCARBON EMISSIONS<sup>(7-2)</sup>FIGURE 10. OXIDES OF NITROGEN (NO<sub>x</sub>)<sup>(7-2)</sup>

FIGURE 7-11. COMPARISON OF SMOKE EMISSION CHARACTERISTICS<sup>(7-2)</sup>FIGURE 7-12. COMPARISON OF COMBUSTOR OUTER LINER TEMPERATURE<sup>(7-2)</sup>

8. DEMONSTRATION CRUISE OF USS SCOTT, DDG-995  
(Reference 8-1)

Summary

The USS Scott, DDG-995, burned shale DFM during six days at sea plus five days in port during a period from 11 June to 21 June, 1984.

The USS Scott has four LM2500 gas turbines as main propulsion engines and three DDA 501-K17 ship service generators. Ship fuel tanks that supply two propulsion engines and two ship service generators were cleaned, then filled with the shale DFM. DFM was used for the other two main propulsion engines and the other generator.

During six days at sea the USS Scott was operated through all customary modes of operation. Total operating time for the LM2500 engines was 119 hours. The operating time on the 501-K17 ship service generator was longer, at 166 hours, as it included five days in port and six days at sea. Total shale DFM consumption was 146,000 gallons.

Performance and operation with shale DFM was not measurably different from that with DFM, with no measurable performance change or observable engine deterioration.

Objective

The objective of this shale DFM demonstration was to compare performance and engine deterioration when burning shale DFM with those when burning DFM under identical conditions.

Procedure

Test Schedule

NAVSES was tasked by DTNSRDC to participate in an at-sea shale DFM demonstration aboard the USS Scott. The demonstration, to evaluate the fuel's compatibility with the USS Scott's gas turbine engines, was performed during the period from 15 June to 21 June, 1983, in the early phase of a six-month deployment during transit between Norfolk, VA, Mayport, FL, and San Juan, Puerto Rico. Two NAVSES representatives rode the USS Scott and monitored plant performance under the stipulation that no specific test runs would be performed and that data gathering would be accomplished without interfering with the ship mission. This restriction had the advantage that the information gathered represents the actual mission profile, and the disadvantage

that tests at specific, preselected data points could not be repeated at intervals during the demonstration.

172,000 gallons of shale DFM were transferred by barge on 15 May from the NAVSSES Philadelphia, PA storage facility to the Norfolk Naval Station, Craney Island Alpha Pier. After shipboard fuel tanks on the USS Scott had been cleaned, the shale DFM was loaded into four aft-port fuel tanks, four mid-bank starboard tanks, and two aft service tanks as storage/service tanks. The engines dedicated to these tanks, which burned the shale DFM, were two LM2500 main propulsion engines, GTM-1A and GTM-2A, and two 501-K17 ship service generators, SSGTG No. 2 and SSGTG No. 3. Although SSGTG No. 3 burned shale DFM, it was not designated as a test engine.

### Instrumentation

Prior to the test, and after completion of the test, the two LM2500 test engines and the DDA 501-K17 test engine were inspected with borescopes. No effects of the shale-fuel test were observed.

Turbine flowmeters were installed to measure fuel flow to the two LM2500 engines, and a wobble-plate flowmeter was installed to measure fuel flow to the 501-K17 engine. Meters provided volumetric readouts and had totalizers. All other engine data were read from existing ship instruments, which had been calibrated several weeks prior to the demonstration. Data monitoring and acquisition involved hand recording of parameters from the demand display on the local operating console in the aft engine room. Ambient temperatures, barometric pressure, and relative humidity were obtained from bridge instruments.

### Operating Schedule

The demonstration consisted of six days of routine in-transit, at-sea operation of the propulsion system and electric plant and five days of in-port electric plant operation. All demands were considered normal. During the at-sea period all propulsion plant operational modes were exercised including full power, split plant, and trail shaft.

Figure 8-1 shows the time-temperature profile for the main propulsion turbines over the demonstration period, the plotted temperature being the inlet gas temperature to the power turbine. The weighted average power for the demonstration was 7800 hp with a range of powers from 1000 to 19,000 hp.

Figure 8-2 shows the total electrical load of the ship service generators throughout the cruise. Throughout the period the generator load ranged from 1,000 to 1,200 kW per generator.

Table 8-1 lists the hours of full power, split plant, and trail shaft operation for the main propulsion engines during the demonstration run.

Table 8-2 lists the total fuel burned by each engine during the demonstration.

### Engine Performance

#### LM2500 Main Propulsion Engines

Forty four sets of data were recorded for each main propulsion engine during the trial period. Split plant and trail shaft modes were selected for data points because engine power can be measured accurately for those conditions. Shaft power was corrected through the gear and standardized for intake and exhaust duct losses of 4 in. and 6 in. water, respectively, 100 F air inlet temperature, 29.92 in. Hg barometric pressure, dry air, and a fuel low heat value of 18,400 Btu/lb.

Figure 8-3 shows specific fuel consumption (SFC) plotted against brake horsepower (BHP) for the LM2500 engines fired with shale DFM. Most data points in Figure 8-3 fall in the upper limits of the nominal estimated band of engine performance. This band is defined as the fuel consumption bounds of a standard engine for the powers and speeds run. A plus-five-percent band represents the normal upper variation in standard engine parameters.

#### DDA 501-K17 Ship Service Gas Turbine Generator Performance

Figure 8-4 shows the relation of turbine inlet temperature to generator electric power output for the 501-K17 ship service generators. The data for SSGTG No. 1 were obtained with petroleum DFM; the data for SSGTG No. 2 and 3 were obtained with shale DFM. Two distinct bands of data are shown. The upper band is the normal condition while supplying bleed air, and the lower band is the normal condition without air bleed. It can be seen from Figure 8-4 that SSGTG No. 2 assumed the bleed load when it was on line, and SSGTG No. 1 assumed the bleed load at other times. The lines through the data points are the "standard" engine conditions.

#### Auxiliary Operation

Operation of fuel system was routine through the trial. The shale DFM was transferred, purified, pumped, and heated without any problems in operation or maintenance of the equipment.



### Analyses of Shale DFM

Table 8-3 shows the analysis of a sample of shale DFM used for the USS Scott demonstration. The fuel met the MIL-F-16884G specification and was very clean.

Table 8-4 compares values of sediment and water for shale DFM samples taken before and after the purifier. The purifier reduced the sediment from 1.3 to 0.5 mg/l, and reduced the water from 152 to 29 ppm.

Table 8-5 summarizes analyses of shale DFM samples taken before and after the coalescer, and before and after the purifier. The only significant differences among the ten samples are in the gravimetric sediment content and the sodium content.

### Conclusions

The performance of the LM2500 and 501-K17 gas turbine engines when burning shale DFM was not measurably different from that when burning petroleum DFM.

There was no visible change in condition of engine components as the result of burning shale DFM.

The demonstration was not long enough to evaluate the effect of shale DFM on engine life. In every other respect the shale DFM proved to be equivalent to petroleum DFM.

### Reference

- 8-1. Ritz, Walter T., USS Scott (DDG-995) Shale Oil Demonstration, Final Report, Naval Ship Systems Engineering Station Project T-1380, October 1983.

TABLE 8-1. USS SCOTT SHALE OIL DEMONSTRATION, LM2500 GAS TURBINE  
MODE SUMMARY, 15-21 JUNE 1983 (Ref 8-1)

MODE	TOTAL TIME, HOURS	PERCENTAGE OF TIME
Full power, four engines	10	9
Split plant, 1A, 2A or 1B, 2B	63	59
Trail shaft, one engine	34	32

TABLE 8-2. USS SCOTT SHALE OIL DEMONSTRATION, FUEL CONSUMPTION  
DISTRIBUTION BY ENGINE (Ref 8-1)

Engine	Consumed during transit 15-21 June 1983 Gallons
GTM 1A	23,000
GTM 1B	60,000
SSGTG No. 1	17,000
SSGTG No. 3	22,000
Total	122,000
	Consumed in port 12-21 June, 1983
SSGTG No. 2 and 3	24,000
Total consumed	146,000
Remaining at end of test	24,000
Total shale DFM at start	172,000

TABLE 8-3. ANALYSIS OF SHALE DFM USED FOR USS SCOTT DEMONSTRATION CRUISE

	REQUIREMENT MIL-F-16884G	SHALE DFM
Appearance	Clear & Bright	Clear & Bright
Distillation		
Initial Boiling Point, °F	-	360
50% Point, °F	-	510
90% Point, °F	675(max)	563
End point, °F	725(max)	587
Flash point, °F	140(min)	168
Pour point, °F	20(max)	-15
Cloud point, °F	30(max)	0
Viscosity at 100°F, Kinematic/Centistokes	1.8-4.5	2.70
Carbon Residue on 10 percent bottoms, percent	0.20(max)	0.07
Sulfur, percent	1.00(max)	0.01
Corrosion at 212°F	1(max)	1A
Ash, percent	0.005(max)	0.001
API Gravity, 60°F	Record	38.4
Demulsification, minutes	10(max)	0.5
Acid Number, mg KOH/gm	0.30(max)	0.01
Neutrality	Neutral	Neutral
Aniline Point, °F	Record	152
Sediment & Water, %	0.010max	0.001
High Heating Value, btu/lb		19,790
Low Heating Value, btu/lb		18,550

TABLE 8-4. FUEL CONTAMINENTS BEFORE AND AFTER PURIFIER, USS SCOTT DEMONSTRATION CRUISE (8-1)

	<u>F. O. PURIFIER SUCTION</u>	<u>F. O. PURIFIER DISCHARGE</u>
Gravimetric Sediment (mg/l)	1.3	0.5
Sodium (ppm)	0.15	0.13
B.S & W (%)	<0.005	<0.005
Total Water (ppm)(K.F.)	152	29

TABLE 8-5. ANALYSES OF TEN SHALE DFM SAMPLES  
From Reference 8-1

Sample Number	1	2	3	4	5	6	7	8	9	10
Appearance	C&B*	C&B	C&B	C&B	C&B	C&B	C&B	C&B	C&B	C&B
Flash Point	178	154	150	160	170	140	164	144	162	156
Pour Point (°F)	-10	-5	-10	-15	-5	-10	-10	-10	-5	-10
Cloud Point (°F)	6	8	10	10	8	6	10	8	12	12
Lower Heating Value (BTU/lb)	18,520	18,530	18,530	18,530	18,520	18,520	18,520	18,530	18,520	18,530
Viscosity @100°F (cs)	2.98	2.98	2.96	2.92	2.88	2.91	2.90	2.89	2.95	2.90
Sulfur (%)	0.04	0.04	0.05	0.05	0.06	0.05	0.05	0.05	0.05	0.03
Specific Gravity @60°F	0.836	0.836	0.836	0.836	0.836	0.836	0.836	0.836	0.836	0.836
API Gravity (API°)	37.7	37.8	37.8	37.8	37.7	37.7	37.7	37.8	37.7	37.8
Total Water (%)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Gravimetric Sediment (mg/l)	4.8	2.2	0.8	1.4	1.4	8.0	3.4	1.6	1.8	3.0
Sodium (ppm)	0.05	0.05	0.07	0.10	0.10	0.19	0.24	0.05	0.07	0.05

\*Clear and Bright

Sample	Description
1	EM02 #1 F/O Coal 0915 6/15/83
2	#2ER Main Prop F.O. After Coal 6/16/83
3	#2ER Daily After Coal Sample 6/18/83
4	#2ER Coal 6/19/83
5	Aux #2 #2 F.O. Purifier Sample after F.O. Purifier 6/20/83
6	Aux #2 #2 F.O. Purifier Sample Before F.O. Purifier 6/20/83
7	Aux #2 #2 F.O. Purifier Sample Before F.O. Purifier 6/20/83
8	ER#2 Fuel System Sample After Coal 6/20/83
9	Aux #2 #2 F.O. Purifier Sample After F.O. Purifier 6/20/83
10	#2ER Coal Test Sample to Engine 6/21/83

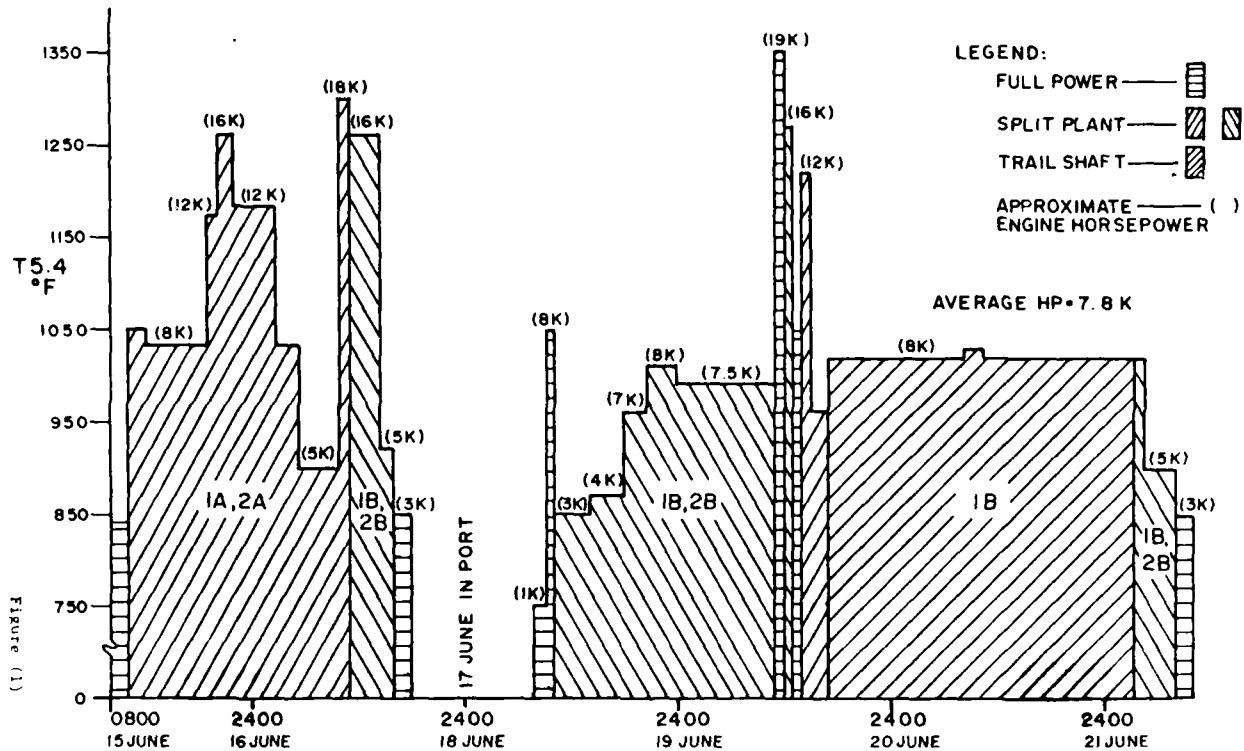


FIGURE 8-1. VARIATION OF POWER TURBINE INLET TEMPERATURE (T5.4) WITH TIME FOR LM2500 MAIN PROPULSION GAS TURBINES, USS SCOTT (DD-995) SHALE OIL DEMONSTRATION. (Ref 8-1)

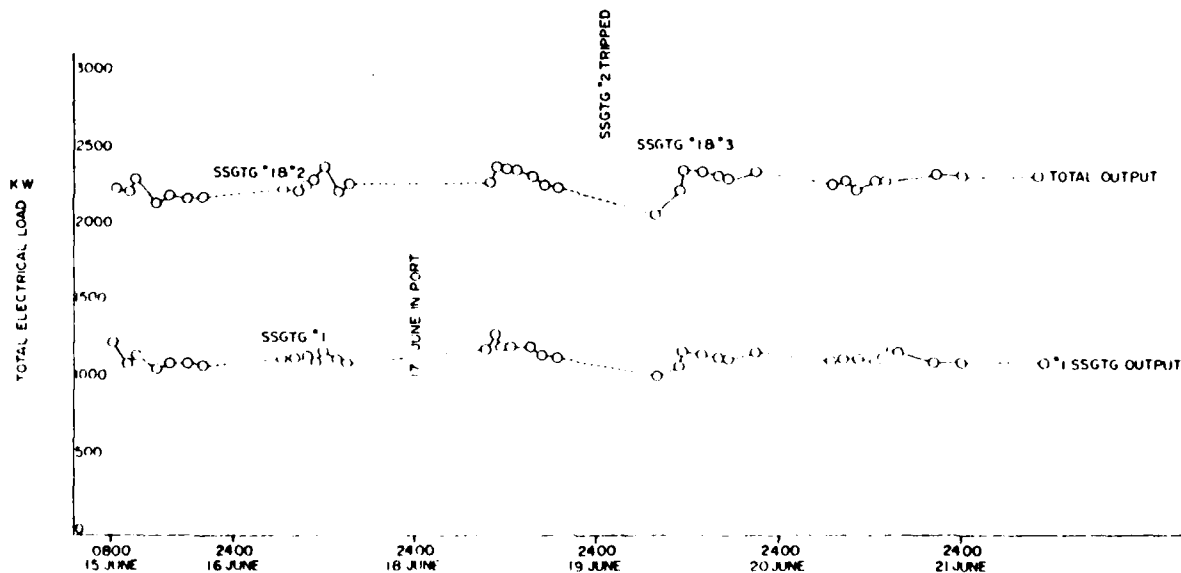


FIGURE 8-2. VARIATION OF ELECTRIC LOAD WITH TIME FOR 501-K17 SHIP SERVICE GAS TURBINE GENERATORS, USS SCOTT (DDG-995) SHALE OIL DEMONSTRATION (Ref 8-1)

# USS SCOTT SHALE OIL DEMONSTRATION MAIN ENGINE PERFORMANCE SFC VS. BHP

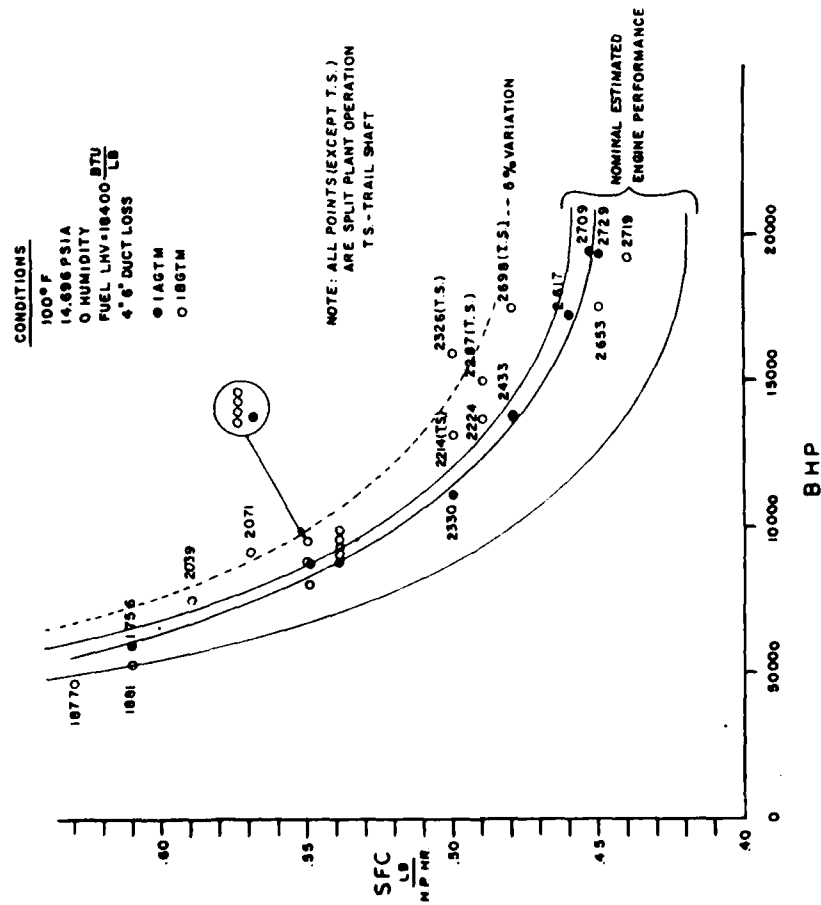


FIGURE 8-3. RELATION OF SPECIFIC FUEL CONSUMPTION TO  
BRAKE HORSEPOWER FOR LM2500 MAIN  
PROPULSION ENGINES, USS SCOTT, DDG-995  
(Ref 8-1)

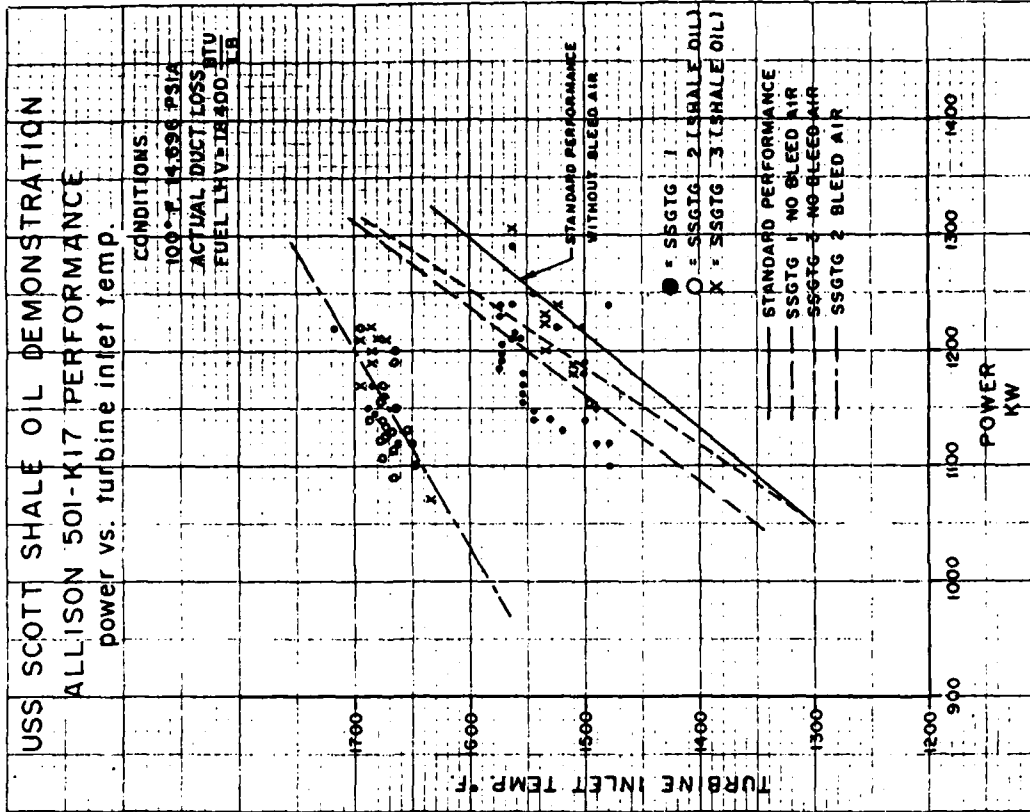


FIGURE 8-4. RELATION OF POWER TURBINE INLET TEMPERATURE  
TO ELECTRIC POWER OUTPUT FOR ALLISON  
501-K17 SHIP SERVICE GENERATORS  
(Ref 8-1)

## 9. TESTS OF NAVY AIRCRAFT GAS TURBINES

### Introduction

The Naval Air Propulsion Center (NAPC) has program responsibility for development and evaluation of Navy aircraft engines and fuels. Their program has included tests of typical aircraft turbine engines with test fuels having a wide range of properties, to evaluate the effects of fuel properties on engine performance, reliability, life, and maintenance. As part of the 100,000 bbl shale oil program, shale JP-5 fuel properties were evaluated and full-scale engine tests were run with four engines. Later, in investigations of the effects of fuel composition on hot-section components of six engines, ten fuels, including shale JP-5, were burned in combustor rig tests.

### Effects of Fuel Properties on Aircraft Gas Turbines (Reference 9-1)

#### Objectives

The objective of this project was to determine the effects of fuel properties on engine performance, life, reliability, and maintenance.

#### Approach

Ten fuel blends, having a wide range of properties, were used in six Navy aircraft gas turbine combustor rig tests. The ten fuels included JP-5, DFM, a 50-50 blend of DFM and JP-5, blends of JP-5 with aromatic blending stock and shale JP-5. Aromatic content varied from 15 to 35 percent, and fuel hydrogen content varied from 12.8 percent to 13.8 percent.

Combustors for the following Navy engines were evaluated to determine their sensitivity to fuel characteristics:

General Electric	F404, T700
Allison	T56
Pratt and Whitney	TF30
Garrett	T76
Lycoming	T53

#### Results and Conclusions

The principal differences in combustor operation when using the experimental fuels was in combustor metal temperatures and in altitude relight capability. Combustor metal temperatures correlated

well with fuel hydrogen content, with fuels of lower hydrogen content causing higher metal temperatures. This relation has been observed in previous tests carried out under NASA and Air Force programs and occurs with all operational military and commercial gas turbines. Higher metal temperatures usually imply shorter combustor life.

Altitude relight capability for DFM was poor, with a loss of ignition altitude of 15,000 to 20,000 ft compared with JP-5. This is attributed to the higher viscosity and lower volatility of DFM, resulting in poorer atomization and less fuel vaporization under relight conditions.

Shale JP-5, provided from the 100,000 bbl project, had somewhat better altitude relight characteristics than the petroleum JP-5, but performance was otherwise identical. The difference was found to be the result of a flatter distillation curve for the shale JP-5, with a higher proportion of volatile compounds having low boiling temperatures.

#### Reports to be Issued

Reports covering results of the multi-fuel engine tests have not yet been issued. However, the following reports have been approved by NAPC and should be issued in the near future.

Vogel, R., "Effect of Fuel Composition on Navy T56 Hot Section Components", Detroit-Diesel-Allison Div. of General Motors, Nov. 1983. NAPC-PE-88C.

Rutter, Steve, "Effect of Fuel Composition on T53-L13B Hot Section Components", Avco-Lycoming, NAPC-PE-92C, Nov. 1983.

Beal, G. W., "Effects of Fuel Composition on Navy Engine Hot Section Components", by G. W. Beal, Pratt and Whitney Aircraft Govt Products Div. NAPC-PE-74C.

Reports on the Garrett and General Electric projects have not yet been submitted to NAPC for approval.

The above information was obtained from Peter Karpovich, of NAPC, in a telephone discussion with H. R. Hazard, of Battelle, on 1 December, 1983.



Evaluation of Shale JP-5 for Navy Aircraft Use  
(Reference 9-2)

Introduction

Shale JP-5 was evaluated as a fuel for both aircraft gas turbines and diesel engines. The evaluations included detailed determination of shale JP-5 properties, fuel system simulator and component testing, a combustor rig test, full-scale tests of four Navy aircraft gas turbines, and tests of a number of diesel engines.

Table 9-1 lists the participants in the shale JP-5 evaluations. The evaluations of JP-5 properties, fuel simulator, and component testing, and full-scale gas turbine engine tests were directed by NAPC. A NAPC report, Reference 9-2 summarizes these evaluations. Because this is a concise, complete report, it is reproduced as Appendix 9-A to this section.

The diesel engine evaluations were coordinated by NAPC and were carried out by a number of participants directed by MERADCOM, DOE, EPA, or independently. The results of diesel engine evaluations appear in other sections of this report, under the the appropriate agency. In general, the properties of shale JP-5 are similar to those of No. 1 diesel fuel, and it proved to be a completely satisfactory fuel for all diesel engines in which it was evaluated.

Objective

The objective of this work was to evaluate the acceptability of shale JP-5 for Navy aircraft use.

Approach

The physical and chemical properties of the shale JP-5 were determined in detail. A combustor rig test to compare a petroleum JP-5 directly with the shale JP-5 was carried out using a Pratt and Whitney TF30-P-412 combustor, followed by full-scale tests of an Allison T63-A-5A engine, an Allison T56-A-14 engine, a General Electric TF34-GE-400 engine, and a Pratt and Whitney TF30-P-414 engine. Results of tests with shale JP-5 were compared with results of tests with JP-5.

Results and Conclusions

The results of NAPC shale JP-5 evaluations are summarized in detail in Reference 9-2, which is appended to this section as Appendix 9-A.

The following conclusions are quoted from Reference 9-2:

- "1. The initial laboratory quality assurance evaluation demonstrated that the fuel conformed to all the requirements of Specification MIL-T-5624L with the exception of the copper strip corrosion test.
2. Due to the severe processing required to remove fuel-bound nitrogen from shale oil crude, the fuel exhibited low lubricity.
3. The addition of benzotriazole and a corrosion inhibitor Hitec E-515 eliminated any potential copper corrosion and lubricity problems.
4. Fuel thermal stability as measured by Jet Fuel Thermal Oxidation Test (JFTOT) and single tube heat exchanger tests was found to be slightly better than a typical petroleum derived JP-5 fuel.
5. Material compatibility studies showed no significant effect of the oil shale JP-5 fuel on elastomers, fuel tank coatings or tank elements.
6. Overall performance of the oil shale JP-5 fuel in a fully instrumented TF30-P-412 combustor rig demonstrated that the oil shale JP-5 performed essentially the same as a petroleum derived fuel when tested at sea level and simulated altitude conditions.
7. Full scale engine testing at altitude and/or sea level conditions in a turboprop, turboshaft, and two turbofan engines showed no significant difference in performance between oil shale and conventional JP-5 fuel.
8. No environmental problems in operating gas turbine engines on oil shale JP-5 fuel were detected.
9. The fuel exhibited acceptable physical and chemical properties after two years in storage.
10. Additional operation in a variety of commercial power plants uncovered no performance or hardware problems associated with the use of oil shale JP-5 fuel."

#### References

- 9-1. Telephone discussion between Peter Karpovich of NAPC and H. R. Hazard of Battelle, 1 December, 1983. Subject: results of tests to evaluate the effects of fuel properties on Navy aircraft gas turbines.
- 9-2. Karpovich, Peter A., "Acceptability of Oil Shale JP-5 Fuel for Navy Aircraft Use", NAPC Report No. NAPC-PE-52, June 1981.

TABLE 9-1. PARTICIPATING INVESTIGATORS IN THE OIL  
SHALE JP-5 TEST PROGRAM

Laboratory	Fuel Test Program
U.S. Army Research and Technology Laboratories, Ft. Eustis, Virginia	800 SHP Advanced Technology Demonstrator Engine Test
U.S. Army Tank-Automotive Command, Warren, Michigan	Advanced Diesel, AGT 1500 Turbine Engine and Fuel Nozzle Tests
U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia	Material Compatibility
David W. Taylor Naval Ship Research and Development Center, Annapolis, Maryland	Material Compatibility, Storage Stability, Chemical Characterization
Naval Research Laboratory, Washington, D.C.	Toxicity Potential, Chemical Characterization
DOE, Bartlesville, Oklahoma	Diesel Engine Performance
NASA Lewis Research Center, Cleveland, Ohio	Chemical Characterization, Low Temperature Flow Properties
Ford Motor Company, Dearborne, Michigan	Diesel Engine Performance
General Motors Research Laboratories, Warren, Michigan	Diesel Engine Performance
Pratt and Whitney Aircraft Group, East Hartford, Connecticut	TF30 Combustor Rig
Detroit Diesel Allison, Indianapolis, Indiana	T56-A-14 150 Hour Accelerated Endurance Test
General Electric Company, Lynn, Massachusetts	TF34-400 Durability Test

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APPENDIX 9-A

ACCEPTABILITY OF OIL SHALE JP-5 FUEL FOR NAVY AIRCRAFT USE

by

Peter A. Karpovich  
NAPC Report No. NAPC-PE-52  
June, 1981

Appendix 9-A is a photocopy of the text, figures, and tables of the above reference but does not include appendices to the original reference. These appendices were the original reports summarized in this reference.

## INTRODUCTION

Current projections indicate little change in the Navy's heavy dependence upon liquid hydrocarbon fuels. As is the case in the civilian transportation industry, the Navy continues to design and build mobile systems under the implicit assumption that they can be fueled with petroleum-like products. Accordingly, the majority of the planned propulsion system developments as well as those systems currently in operation, which together constitute the mainstay of the Navy's military capability until the turn of the century or later are dependent upon liquid hydrocarbon fuels.

Balancing this requirement against the rapidly depleting and largely foreign reserves of petroleum crude, the use of synthetic fuels to augment the domestic fuel base offers the best long-term assurance of military jet fuel availability. Of the various alternatives to petroleum, such as coal, oil shale and tar sands, oil shale is considered the most attractive source of transportation fuels particularly for a high yield of middle distillate fuel.

In 1974, the Navy was the lead agency for a project to refine and test fuels produced from 10,000 barrels of crude shale oil (reference 1). Although process contamination and low severity process conditions resulted in a fuel with some properties not conforming to the JP-5 specification requirements (reference 2), this initial full scale refinery experiment successfully demonstrated the feasibility of using crude shale oil as a feedstock for military fuels.

As part of a joint Department of Defense (DOD)/Department of Energy (DOE) follow-on program, 100,000 barrels of shale oil crude (Shale II) was produced at Anvil Points, Colorado by the Paraho process. The crude was refined in late 1978 at the Standard Oil Company (SOHIO) refinery in Toledo, Ohio into a spectrum of DOD fuels using state-of-the-art processing techniques. Reference 3 authorized Naval Air Propulsion Center (NAPC) personnel to implement Work Unit Plan Number 616 which provided for the test and evaluation of the JP-5 fraction obtained from the SOHIO refinery. The subject of this report is the investigation of oil shale derived JP-5 fuel and its compatibility with Navy aircraft systems. Testing of the fuel included standard specification tests, fuel system simulator, engine and airframe component tests and full scale engine tests. Some specific areas and details of the investigation are contained in this report as appendices. Each appendix is a study in itself and the information contained in the appendices is summarized in the body of this report.

## CONCLUSIONS

1. The initial laboratory quality assurance evaluation demonstrated that the fuel conformed to all the requirements of Specification MIL-T-5624L with the exception of the copper strip corrosion test.
2. Due to the severe processing required to remove fuel-bound nitrogen from shale oil crude, the fuel exhibited low lubricity.
3. The addition of benzotriazole and a corrosion inhibitor Hitec E-715 eliminated any potential copper corrosion and lubricity problems.

4. Fuel thermal stability as measured by Jet Fuel Thermal Oxidation Test (JFTOT) and single tube heat exchanger tests was found to be slightly better than a typical petroleum derived JP-5 fuel.
5. Material compatibility studies showed no significant effect of the oil shale JP-5 fuel on elastomers, fuel tank coatings or tank sealants.
6. Overall performance of the oil shale JP-5 fuel in a fully instrumented TF30-P-412 combustor rig demonstrated that the oil shale JP-5 performed essentially the same as a petroleum derived fuel when tested at sea level and simulated altitude conditions.
7. Full scale engine testing at altitude and/or sea level conditions in a turboprop, turboshaft and two turbofan engines showed no significant difference in performance between oil shale and conventional JP-5 fuel.
8. No environmental problems in operating gas turbine engines on oil shale JP-5 fuel were detected.
9. The fuel exhibited acceptable physical and chemical properties after two years in storage.
10. Additional operation in a variety of commercial powerplants uncovered no performance or hardware problems associated with the use of oil shale JP-5 fuel.

#### RECOMMENDATIONS

1. Ongoing evaluations of the JP-5 fuel obtained from the Shale II project be continued.
2. Information obtained from this investigation be used to improve refinery process techniques specifically tailored towards shale oil crude.
3. Samples of fuels produced from non-traditional crude sources such as oil shale, coal, tar sands and heavy crude be obtained and thoroughly analyzed in order to initiate a data base on alternate fuels.

#### DESCRIPTION

1. The shale oil processing scheme utilized by SOHIO is shown in Figure 1. Because of the very high organically bound nitrogen in the crude shale oil, about 20,000 ppm nitrogen (N), the crude requires a different processing scheme than is normally required for petroleum crude. To remove the organically bound nitrogen, the initial processing step employs high pressure catalytic hydrogenation at elevated temperatures with a high consumption of gaseous hydrogen. These process conditions produce a reaction between the gaseous hydrogen and the organically bound nitrogen, which result in the formation of ammonia (NH<sub>3</sub>) and nitrogen free hydrocarbons. Following the hydrogenation step the organically bound nitrogen content is approximately 2,000 ppm. This level must be further reduced to less than 10 ppm N in order to have a thermally stable fuel. The residual organically bound nitrogen is removed by sulfuric acid treatment (90 to 92 percent H<sub>2</sub>SO<sub>4</sub>) followed by clay treatment to remove trace H<sub>2</sub>SO<sub>4</sub> and/or other heteroatoms that may be in the finished fuel as undesirable by-products.

2. The Toledo hydrotreating run lasted from 1 November to 4 December 1978. The stored raw JP-5 was acid/clay treated during the month of January 1979. Approximately 260,000 gallons of finished JP-5 was produced and shipped to Rickenbacker AFB, Columbus, Ohio for storage. The fuel was distributed under the direction of NAPC personnel to various laboratories for testing. A list of the military and commercial laboratories that received shipments of Shale II fuel and a summary of the test program that each laboratory conducted is shown in Table I.

#### ANALYSIS OF RESULTS AND DISCUSSION

##### 1. Analytical Assessment of Basic Fuel Properties

a. As was previously stated, the U.S. Navy has conducted two experiments to produce middle distillate fuels from shale oil crude. Both projects used crude oil produced by the Paraho retorting process but different refinery processes were used. The Shale I refining operation produced JP-5 by delayed coking followed by fractionation and mild hydrotreatment. The Shale II exercise used hydrocracking, fractionation, and acid treatment to make JP-5. Consequently, the two shale products obtained were quite different from each other. Furthermore, the shale products are distinctly different from petroleum derived jet fuel since simple refining techniques (fractionation plus mild hydrofinishing in some cases) are typical. Work performed at the Naval Research Laboratory shows the following comparison of JP-5 fuels derived from oil shale and petroleum:

(1) Elemental Analyses - Table II lists some composition data for Shale I, Shale II, and petroleum products. The noteworthy feature for elemental composition is the high nitrogen concentration for Shale I JP-5. Shale derived fuels typically contain considerable amounts of nitrogen compounds but the Shale II fuel was quite low due to the removal of nitrogen compounds by extensive acid treatment.

(2) n-Alkane Content - Table II also lists the content of individual n-alkanes as well as the total. The shale fuels are high in n-alkanes. However, the Shale II process, which used high pressure catalytic hydrocracking, gave a JP-5 with less n-alkanes (22 percent). The lower content compared to Shale I results from isomerization during the hydrocracking refining step. The data listed for a petroleum sample is typical of several JP-5's which have been analyzed.

(3) Hydrocarbon Classes - Table III lists the classes of hydrocarbons found in jet fuels. The amounts of Shale II product are compared with a petroleum JP-5. The major classes for both fuels are saturates and monoaromatics. The aromatic content for petroleum JP-5's are frequently less than that shown in Table III.

(4) Characterization of Aromatic Fractions - The aromatic fractions were characterized by nuclear magnetic resonance (nmr) and field ionization mass spectrometry (FIMS). Parameters calculated from nmr for the average aromatic molecule are tabulated in Table IV. The parameters are fairly similar but the number of naphthene rings per aromatic molecule is somewhat higher for Shale II than for the other two fuels. This is an indication of increased tetralin content.

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This latter finding was supported by the FIMS data. Figure 2 displays mass spectra for Shale II and a petroleum JP-5. Peaks labeled B represent substituted benzenes and those marked with a T indicate tetralins, the two major classes of monoaromatics. Note that benzenes predominate for the petroleum fuel but that tetralins total about the same amount as benzenes for the Shale II JP-5.

b. Specification testing performed at NAPC and the Air Force Wright Aeronautical Laboratories (AFWAL) (Table V) showed that the fuel conformed to all of the requirements of MIL-T-5624L (reference 2) except for copper strip corrosion. Since this fuel was scheduled to be evaluated in several engine tests and it was possible that a fuel with poor corrosion properties would attack critical engine components, an investigation was initiated to determine the cause of the corrosion and recommend a solution. Laboratory analyses (reference 4) indicated that the presence of free sulfur and mercaptan sulfur introduced either during the acid treatment process or from a contaminated anti-oxidant additive was the probable cause for failure of the fuel in the copper strip corrosion test. Additional testing performed at NAPC and David W. Taylor Naval Ship Research and Development Center to learn more about the copper corrosion problem is reported in Appendices A and B, respectively. One significant conclusion drawn from these studies was that corrosion of copper and other metals did not occur when the fuel was maintained below 100°C. In a previous investigation concerning copper contamination of fuel (reference 5) it was found that the use of benzotriazole was successful in controlling the migration of copper into fuel by passivating the metal surface. Tests conducted at NAPC determined that the addition of 2 ppm of benzotriazole to the oil shale JP-5 prevented the corrosion of copper in the ASTM D130 test. Based on these results, it was decided to add benzotriazole to the bulk fuel prior to engine testing.

c. In view of the unusual chemistry of synthetic fuels and the problems encountered with the thermal stability of Shale I JP-5 (reference 1), the storage stability of Shale II fuel was thoroughly evaluated. After two years storage the fuel showed an acceptable level of peroxide content, less than 8 ppm (1 meq), and the thermal stability was still above the minimum acceptable temperature limit of 260°C as defined by JFTOT testing. The data are summarized in Table VI and plotted in Figures 3 and 4. The erratic behavior of the peroxide build up and depletion is believed to be the dynamics of an oxidation process in the presence of an oxidation inhibitor.

d. Evaluation of the compatibility of oil shale JP-5 with polymeric elastomers, polysulfide sealants and a polyurethane coating (reference 6) showed no significant differences between Shale II fuel and petroleum derived JP-5. Expected differences caused by the ratio of unusual aromatic compounds in shale fuel were not evidenced.

## 2. Fuel System Simulator and Component Testing

a. Lubricity differences among fuels are generally related to the degree of hydrotreatment of the crude. The removal of chemically active species to upgrade the thermal stability of fuels is invariably associated with poorer lubricity. The severe processing required to remove fuel-bound nitrogen from shale oil in this experiment produced a poor lubricity fuel. Results obtained using the Ball on Cylinder Machine (BOCM) are shown in Table VII. Experience (reference 7) has shown that the addition of corrosion inhibitors can improve the lubricity of fuels. Results summarized in Table VII show that the addition of Hitec E-515



to the Shale II fuel improved the lubricity rating to an acceptable level. The current definition of lubricity rating which is based on service experience is:

<u>Wear Scar Diameter (WSD), mm</u>	<u>Fuel Lubricity</u>
WSD $\leq$ 0.42	good
0.43 $\leq$ WSD $\leq$ 0.48	marginal
WSD $>$ 0.49	poor

In order to prevent premature failures of fuel pumps or control system hardware, it was decided to add 30 ppm of Hitec E-515 to the fuel prior to engine testing.

b. Fuel in most high performance aircraft is subject to high thermal stresses resulting from its use as a heat sink. Thermal stability is a measure of the fuel's ability to withstand this stress without degradation. This ability is extremely important in the operation of critical fuel system components including the fuel control, heat exchanger, and fuel injectors. The thermal stability of JP-5 fuel is currently assessed in the JFTOT test (ASTM D 3241) by either a pressure drop across a filter and/or a color-code rating of deposits on the preheater test section. However, neither of these parameters have been correlated to performance or degradation in engine fuel systems perhaps due to the limitations of the JFTOT test. Efforts at NAPC to investigate the long term effects of fuel stability on fuel system operation have led to the development of a Single Tube Heat Exchanger (HX) Test. It appears that this test more realistically simulates actual fuel system operating conditions and more closely defines fuel thermal oxidative stability. A schematic diagram of the test rig is presented in Figure 5. The test section contains a single tube from a typical engine heat exchanger. The fuel inside the heat exchanger tube is heated by lube oil flowing outside and counter current to the fuel. A constant fuel temperature is maintained throughout the test. Any deviation from this temperature is sensed by the controller which signals the lube heater to make an adjustment in the lube temperature. As deposits form on the fuel side the lube temperature increases. Complete operating conditions are described in reference 8. Fuel and lube temperatures are used to calculate the heat exchanger effectiveness coefficient ( $\epsilon$ ) which is plotted as a function of time. The deterioration or decay in the  $\epsilon$  value is a measure of deposit formation in the HX. To simplify the calculations and the interpretation of the data, the only variable in the equation is the lube-in temperature. The fuel-in and fuel-out temperatures are maintained constant. The HX  $\epsilon$  equation is as follows:

$$\epsilon = \frac{T_{f_o} - T_{f_i}}{T_{l_i} - T_{f_i}}$$

Where:  $\epsilon$  = heat exchanger effectiveness coefficient

$T_{f_i}$  = temperature of fuel in (constant)

$T_{f_o}$  = temperature of fuel out (constant)

$T_{l_i}$  = temperature of lube in (variable)

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HX testing of the oil shale fuel and a typical petroleum derived JP-5 fuel was performed at the test conditions listed in Table VIII. The  $\epsilon$  values were plotted versus time and are shown in Figure 6. JFTOT breakpoint temperatures were 274°C (525°F) for the petroleum fuel and 285°C (545°F) for oil shale JP-5. As can be seen from Figure 6, there is a trend for the fuels to cause deterioration of the heat exchanger performance in the order of their thermal stability breakpoint temperature as determined by the JFTOT test (ASTM D 3241). This means that oil shale JP-5 would be less likely to deposit thermal decomposition products in the fuel system. Based on a regression line, a one percent loss in  $\epsilon$  occurred at 158 hours and 1000 hours for petroleum and oil shale JP-5 fuel, respectively. Further details on the HX may be found in reference 8.

c. Since fuel chemical composition (e.g. aromatics) and volatility have a significant effect on combustion system performance, it was decided to conduct comparative testing of petroleum and shale derived JP-5 fuels in a high performance engine combustor. The testing of a Pratt and Whitney TF30-P-412 combustion system included an examination of ignition performance, combustion efficiency and stability, gaseous and smoke emissions, combustor liner and exhaust gas temperature distribution. In all of the testing the shale-derived JP-5 fuel performed essentially the same as the reference fuel, a petroleum-derived JP-5 fuel with the same aromatic content.

3. Full Scale Engine Testing. Evaluation of fuel performance in simulator and component tests provides excellent quantitative data as a function of fuel properties. However, actual full scale engine testing is necessary to determine the acceptability of fuel for Navy aircraft use and to establish correlations between rig and engine test results. The full scale engine evaluation of oil shale II JP-5 fuel consisted of testing in a turboshaft, a turboprop and two turbofan engines.

a. Allison T63-A-5A Engine. An Allison T63-A-5A turboshaft engine was operated on a variety of fuels including oil shale JP-5. Appendix C presents the uncorrected engine performance and exhaust emission data obtained during this evaluation. Comparison of the data shows equivalent exhaust emissions and engine performance for the oil shale and the petroleum derived JP-5 fuel. In a subsequent engine test, peak light-off turbine outlet temperature (TOT) and time to reach 30,000 RPM gas turbine speed were measured for oil shale and conventional JP-5. Results shown in Table IX indicate that the oil shale JP-5 fuel started quicker and provided a slightly higher peak TOT than petroleum derived JP-5 fuel. Inspection of the hot section components after 100 hours of endurance testing showed normal amounts of carbon deposits on the fuel nozzle and ignitor.

b. Allison T56-A-14 Engine. A 150-hour Accelerated Endurance Test at sea level conditions was run at Detroit Diesel Allison Division, Indianapolis, Indiana on a T56-A-14 turboprop engine using oil shale fuel. This test is equivalent to approximately 375 hours of hot section fleet service life. Performance of the engine and the condition of the hot section hardware after testing were essentially equivalent to experience with petroleum JP-5 fuel. In the opinion of Allison engineers, the oil shale JP-5 performed satisfactorily.

c. General Electric Company TF34-GE-400 Engine. In March 1980, an evaluation of the effects of oil shale JP-5 on the transient and steady state operation of a TF34 turbofan engine was initiated. Following 25 Simulated Training Mission (STM) cycles (see Figure 7), on standard JP-5 (see Table X), the engine was operated on oil shale fuel for approximately 141 STM cycles. The results of both

phases of testing are shown in Table XI. No detectable difference in real steady-state performance was noted with the shale fuel. While a 0.6 point gain in Specific Fuel Consumption (SFC) was measured during the shale fuel calibration, the improvement was not supported by thrust or fan speed changes. Fuel flow mismeasurement, evidenced by a negative shift in harness correlation and small increases in  $\eta_{hpt}$  at high power seemed to be the most likely cause of the SFC difference. Transient testing, consisting of starts, bursts, chops and bodie stall tests, also confirmed the quality and stability of the shale derived JP-5. Average cold start and hot restart times were better with the oil shale fuel. Bodie stall testing, run with maximum variable speed constant frequency generator loading failed to induce a stall with either fuel. Because a stall "threshold" was never encountered, the impact of the shale fuel on this parameter could not be quantified. Upon completion of the 141 STM cycles, the engine was removed from the test cell and inspected. The engine hot section was found to be in excellent condition. A post-test calibration of the fuel swirlers (Table XII) showed normal blockage. In the opinion of General Electric engineers (reference 9), the oil shale fuel performed satisfactorily in the TF34-GE-400 engine.

d. Pratt and Whitney TF30-P-414 Engine. An altitude performance and functional test of a TF30-P-414 was conducted at NAPC on oil shale JP-5 and a high aromatic petroleum JP-5 fuel (reference 10). There was no significant difference in engine steady-state performance, ram air altitude restart capability or afterburner operation when using the oil shale and petroleum JP-5 fuels. However, afterburner lights were marginally faster using oil shale JP-5 fuel. There was no significant difference in products of combustion of the TF30-P-414 engine when using either fuel, though the smoke number was marginally higher (worse) for oil shale JP-5. Further details of the test results are found in reference 10.

e. Miscellaneous Testing. Several non-aviation propulsion systems were also operated on oil shale JP-5 fuel and the results are summarized below:

(1) The performance of oil shale JP-5 in a John Deere 6466-T diesel engine (reference 11) was found to be equivalent to the baseline performance with diesel fuel.

(2) Performance of the oil shale fuel in a Cummins Model NTC-400 diesel engine was better than expected as reported by the U.S. Army Tank-Automotive Command (reference 11).

(3) Preliminary results obtained using oil shale JP-5 fuel in an AVCO-Lycoming AGT-1500 combustor test rig (reference 12) indicate no operational problems and better than average performance characteristics.

#### SUMMARY

1. Shale oil holds the key to reducing our dependence on foreign petroleum oil. This investigation has demonstrated that shale oil can be refined into an acceptable jet fuel. The effect of processing and process conditions however were shown to clearly affect fuel properties. In order to insure that the Navy is an informed customer for oil shale products, continued monitoring of production samples will be an ongoing part of the overall Navy Energy Research and Development Plan.

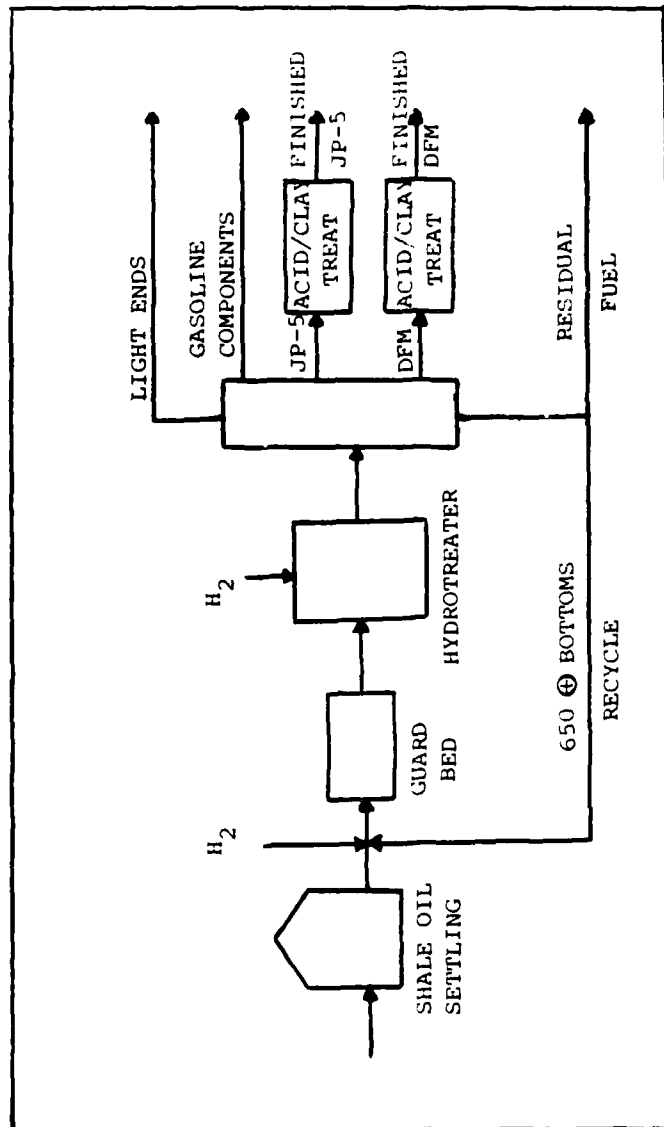
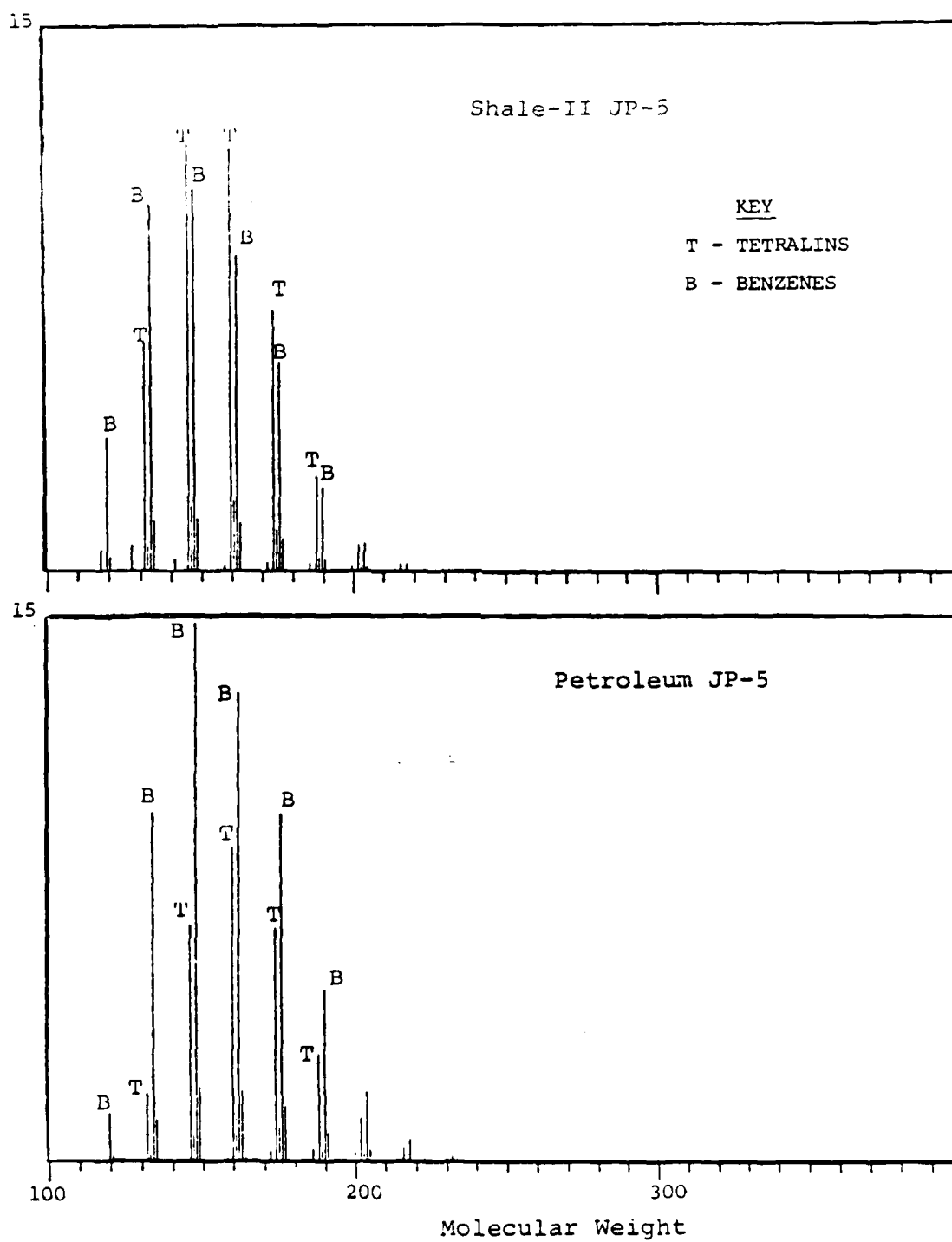


FIGURE 1. SHALE OIL II REFINING PROCESS SCHEME

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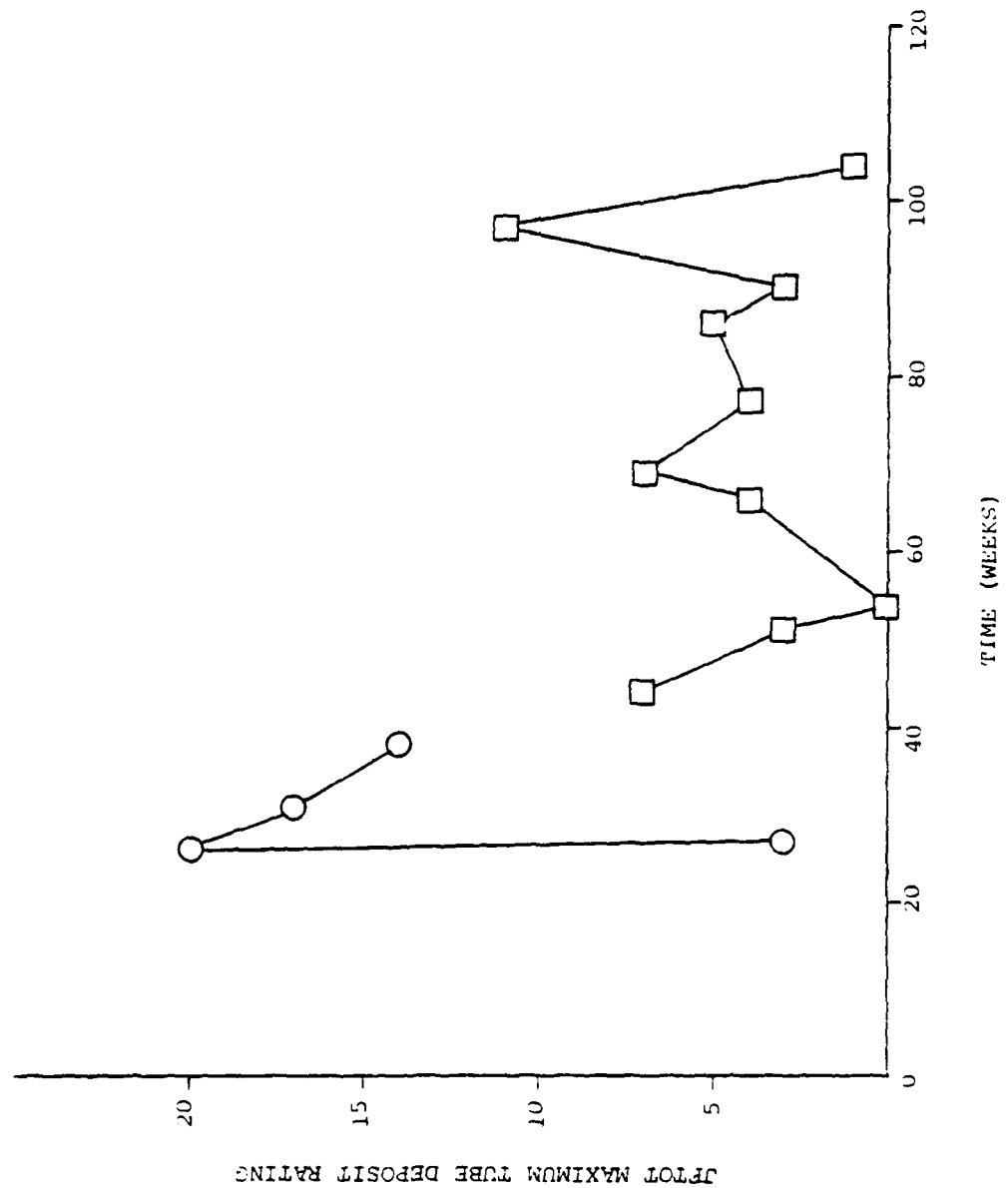
FIGURE 2. COMPARISON OF MONOCROMATIC FRACTIONS OF OIL SHALE AND PETROLEUM DERIVED JP-5 FUELS



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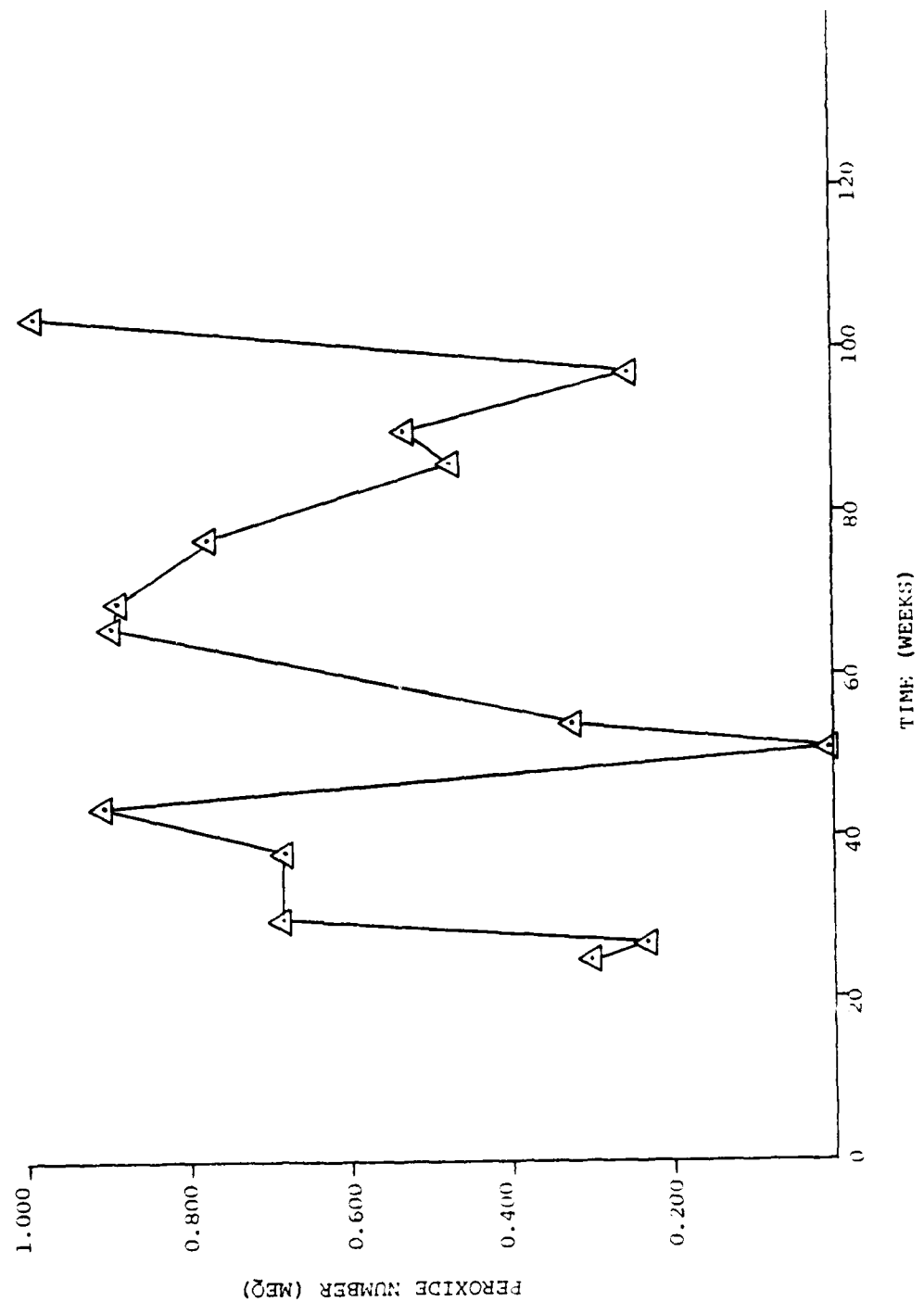
Test Condition  
○ - 282°C (540°F)  
□ - 266°C (510°F)

FIGURE 3. JFTOT RESULTS FOR OIL SHALE II JP-5 FUEL.



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FIGURE 4. PEROXIDE LEVEL OF OIL SHALE II ,P-5 FUEL VERSUS TIME



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FIGURE 5. SCHEMATIC OF SINGLE TUBE HEAT EXCHANGER RIG

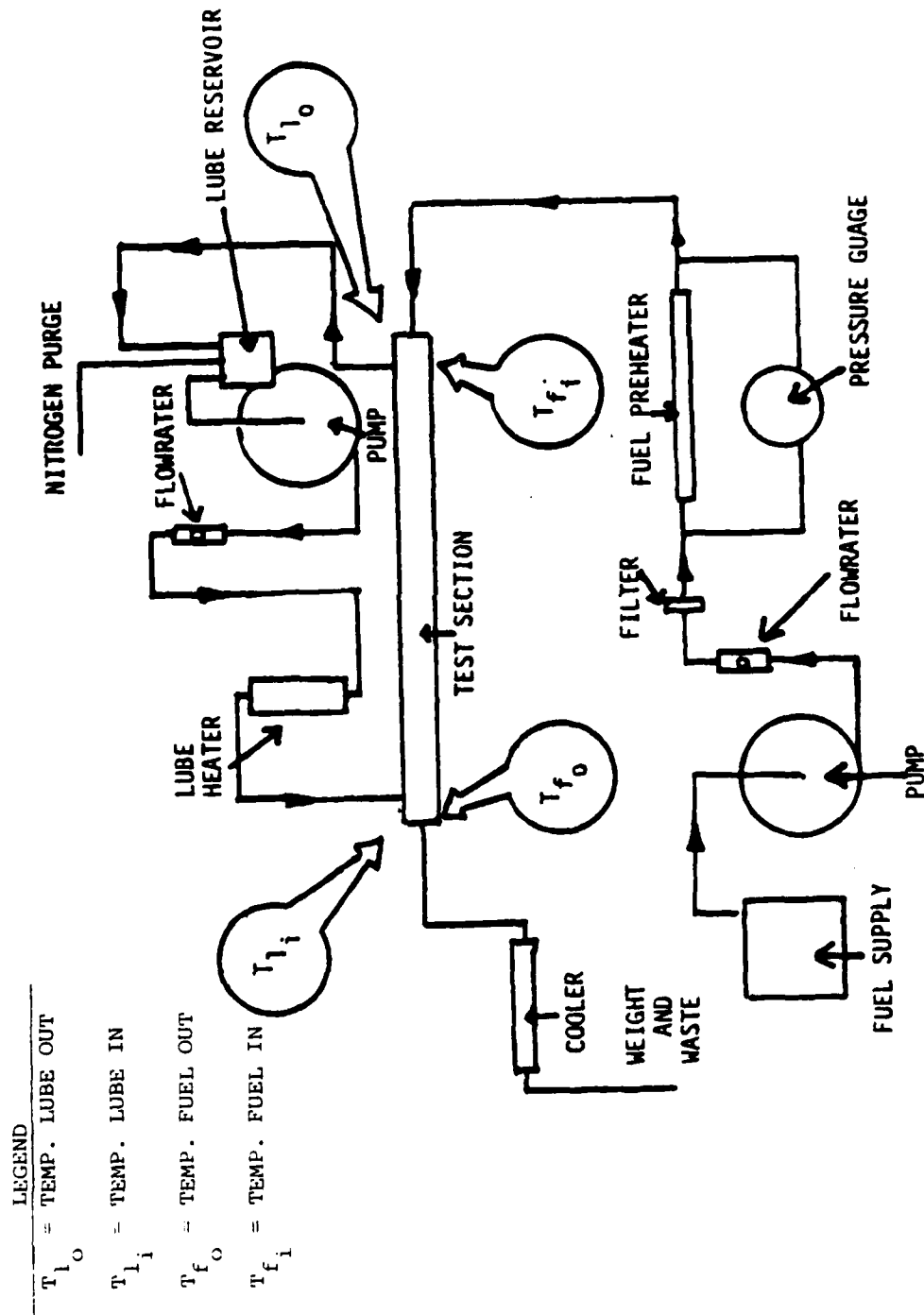
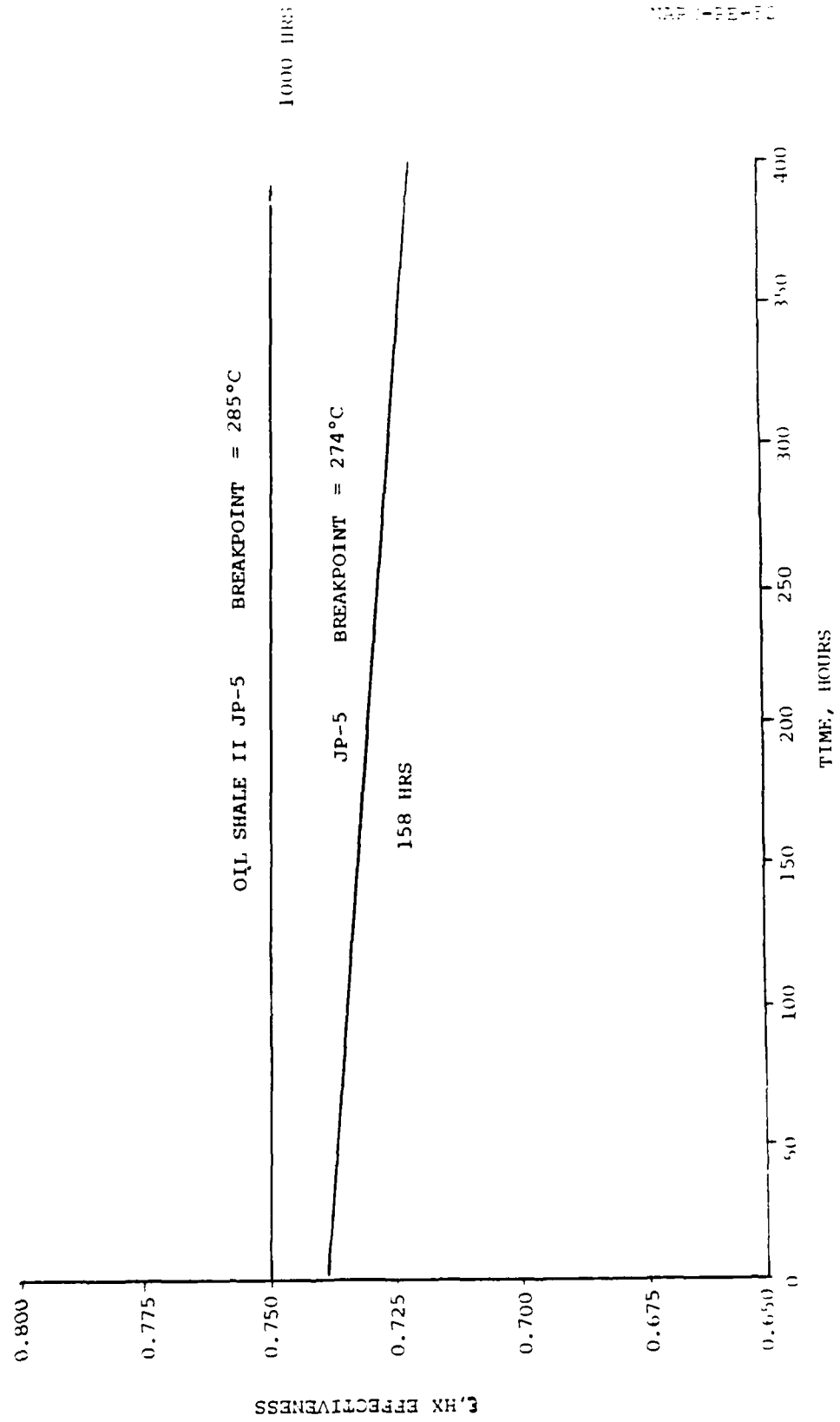


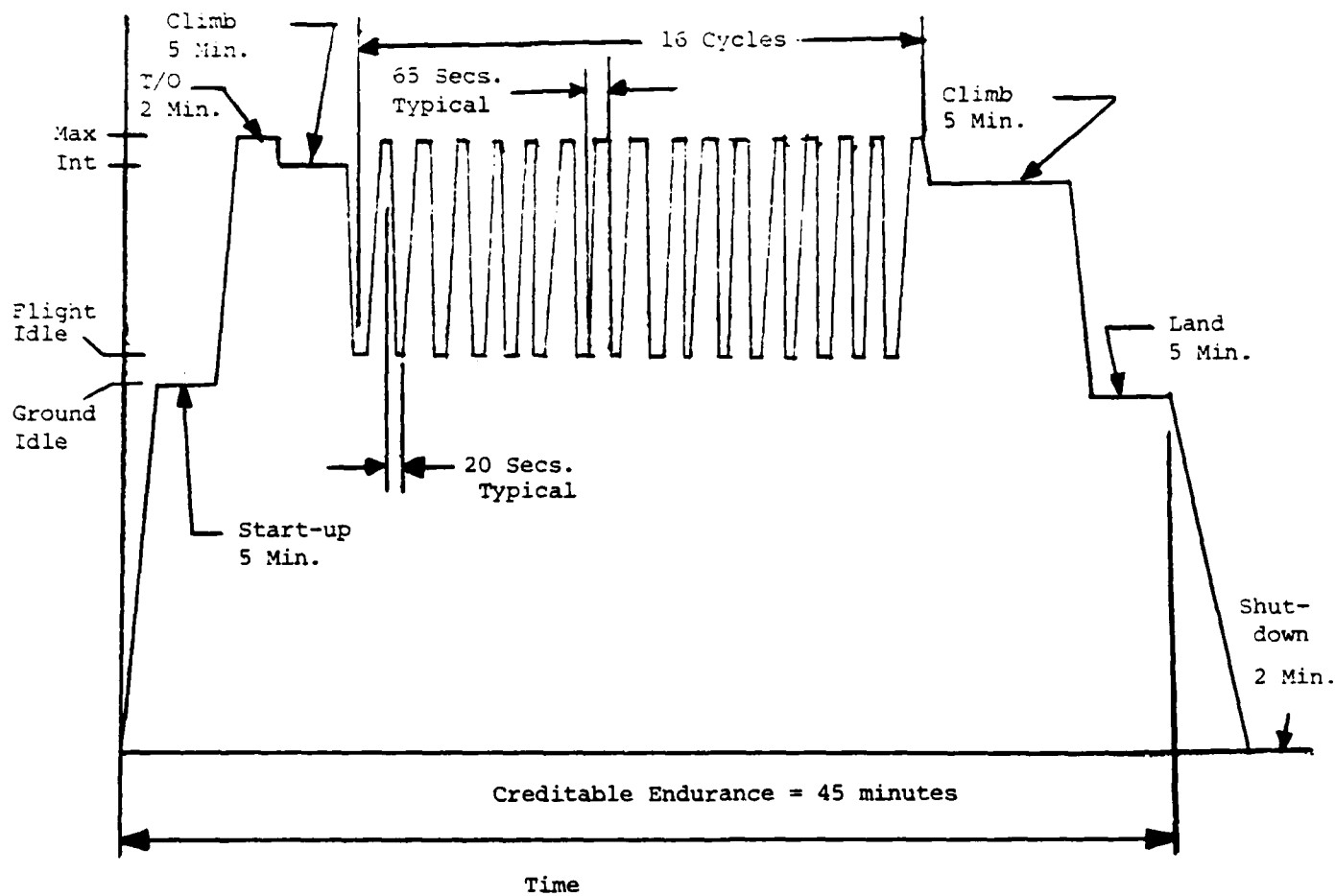


FIGURE 6. LOSS IN SINGLE TUBE HEAT EXCHANGER EFFECTIVENESS VERSUS TIME FOR OIL SHALE II AND PETROLEUM DERIVED JP-5 FUEL.



NOTE: Breakpoint determined by JFTOT test.

FIGURE 7. SIMULATED TRAINING MISSION CYCLE FOR A TF34-GE-400 ENGINE



- 1) Start
- 2) Hold at Idle for 5 minutes (turn bleed on after reaching idle)
- 3) Burst to Max Power (to give  $T_4 = 2285^\circ\text{F}$ )
- 4) Hold at Max Power for 2 minutes
- 5) Decel to Intermediate Power ( $1427\text{--}1437^\circ\text{F } T_5$ )
- 6) Hold at Intermediate Power for 5 minutes
- 7) Chop to Flight Idle ( $13150 \pm 150 \text{ Ng}/\sqrt{\theta_2}$ )
- 8) Hold at PLA setting for 20 seconds
- 9) Burst to Max Power
- 10) Hold at Max Power PLA setting for 65 seconds
- 11) Repeat steps 7-10 15 additional times
- 12) Chop to Intermediate Power
- 13) Hold Inter for 5 minutes
- 14) Chop to Idle
- 15) Hold Idle 5 minutes (at 5 minute point, turn bleed off)
- 16) Shutdown
- 17) Remain at zero rpm for 2 minutes

TABLE I

## PARTICIPATING INVESTIGATORS IN THE OIL SHALE JP-5 TEST PROGRAM

<u>Laboratory</u>	<u>Fuel Test Program</u>	<u>Program Status</u>
U.S. Army Research and Technology Laboratories, Ft. Eustis, Virginia	800 SHP Advanced Technology Demonstrator Engine Test	On-going
U.S. Army Tank-Automotive Command, Warren, Michigan	Advanced Diesel, AGT 1500 Turbine Engine and Fuel Nozzle Tests	On-going
U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia	Material Compatibility	Completed
David W. Taylor Naval Ship Research and Development Center, Annapolis, Maryland	Material Compatibility, Storage Stability, Chemical Characterization	On-going
Naval Research Laboratory, Washington, DC	Toxicity Potential, Chemical Characterization	Completed
DOE, Bartlesville, Oklahoma	Diesel Engine Performance	On-going
NASA Lewis Research Center, Cleveland, Ohio	Chemical Characterization, Low Temperature Flow Properties	On-going
Ford Motor Company, Dearborne, Michigan	Diesel Engine Performance	On-going
General Motors Research Laboratories, Warren, Michigan	Diesel Engine Performance	On-going
Pratt and Whitney Aircraft Group, East Hartford, Connecticut	TF30 Combustor Rig	Completed
Detroit Diesel Allison, Indianapolis, Indiana	T56-A-14 150 Hour Accelerated Endurance Test	Completed
General Electric Company, Lynn, Massachusetts	TF34-400 Durability Test	Completed

TABLE II  
ELEMENTAL COMPOSITION AND N-ALKANE CONTENT OF OIL SHALE  
AND PETROLEUM DERIVED JP-5 FUELS

	<u>Shale-II</u>	<u>Shale-I</u>	<u>Petroleum</u> <u>(typical)</u>
Hydrogen (wt %)	13.7	13.7	13.8
Nitrogen (ppm, wt/vol)	1.0	860	0.4
Sulfur (wt %)	0.04	0.05	0.07
n-alkanes			
C-9	0.1	0.9	0.3
C-10	4.2	3.3	2.1
C-11	7.2	7.5	3.7
C-12	6.1	7.1	3.6
C-13	3.3	6.7	2.9
C-14	0.9	5.1	1.6
C-15	0.3	3.3	0.7
C-16	0.1	2.6	0.1
C-17	<u>0.01</u>	<u>0.3</u>	<u>---</u>
TOTAL	22.2	36.8	15.0

TABLE IIIHYDROCARBON CLASSES OF OIL SHALE AND PETROLEUM  
DERIVED JP-5 FUELS BY LIQUID CHROMATOGRAPHY

	<u>Shale-II</u>	<u>Petroleum</u>
Saturates	73.5 wt %	77.3 wt %
Olefins	2.9	1.2
Monoaromatics	22.5	20.9
Di- and tri-aromatics	1.1	0.6

TABLE IV  
AVERAGE MOLECULAR PARAMETERS OF AROMATICS FOUND  
IN OIL SHALE AND PETROLEUM DERIVED JP-5 FUELS

	<u>Shale-II</u>	<u>Shale I</u>	<u>Petroleum</u> <u>(typical)</u>
Alkyl Substituents/ Molecule	3.2	2.95	2.85
Carbons/Alkyl Substituent	2.0	2.05	2.1
Average Molecular Weight	164	173	172
Average Molecular Formula	$C_{12.2}H_{16.8}$	$C_{13.0}H_{16.8}$	$C_{13.0}H_{16.6}$
Hydrogen (wt. %)	10.6	9.7	9.6
Naphthene Rings/Molecule	0.5	0.35	0.4

TABLE V  
OIL SHALE II FUEL SPECIFICATION TEST RESULTS

Method	MIL-T-5624K, Grade JP-5 Requirements	Test Results	
		NAPC	AFWAL
D 3242	Total acid number, mg KOH/g, max.	0.015	0.001 0.000
D 1319	Aromatics, vol. percent, max.	25.0	24.0 24.4
D 1319	Olefins, vol. percent, max.	5.0	1.6 1.8
D 1266	Sulfur, total weight percent, max.	0.40	0.04 0.000
D 1219	Sulfur, mercaptan, weight percent, max.	0.001	0.01 0.01
D 36	Distillation temperature, deg C (deg F)		
	Initial boiling point	*	186 (366) 181 (358)
	10 percent recovered, max. temp.	205 (401)	193 (380) 192 (378)
	20 percent recovered, max. temp.	*	196 (384) 196 (384)
	50 percent recovered, max. temp.	*	207 (404) 204 (400)
	90 percent recovered, max. temp.	*	232 (449) 230 (446)
	End point, max. temp.	290 (554)	253 (488) 252 (485)
	Residue, vol. percent, max.	1.5	1.2 1.0
	Loss, vol. percent, max.	1.5	0.2 1.0
D 93	Flash Point, deg C (deg F), min.	60 (140)	66 (150) 60 (140)
D 1298	Density, kg/m <sup>3</sup> , min. (°API, max.) at 15°C	788 (48.0)	
D 1298	Density, kg/m <sup>3</sup> , max. (°API, min.) at 15°C	845 (36.0)	807 (43.8) 807 (43.8)
D 1322	Smoke point, mm, min.	19.0	21.0 25.0
D 2386	Freezing point, deg C (deg F), max.	-46 (-51)	-46 (-51) -48 (-55)
D 445	Viscosity, at -34.4°C, mm <sup>2</sup> /s (cSt), max.	-	7.99 7.97
D 240	Heating value, aniline-gravity prod., min.	4,500	6123 6044
or	or net heat of combustion,	10,160	- -
D 2382	cal/g (BTU/lb), min.	(18,300)	(18,561) (18,540)
D 130	Copper strip corrosion, 2 hr. at 100°C (212°F), max.	1b	3b 4a
D 3241	Thermal stability		
	Change in pressure drop; mm Hg, max.	25	0 0
	Preheater deposit code, less than	3	0 1
D 381	Existent gum, mg/100 ml, max.	7.0	0.0 1.0
D 2276	Particulate matter, mg/litre, max.	1.0	0.6 0.1
D 2550	Water separation index, modified, min.	85	98 90
FTM 5327	Fuel System Icing Inhibitor, vol. percent, min.	0.10	0.10 0.21

\* To be reported - not limited.

TABLE VI  
THERMAL OXIDATION AND STORAGE STABILITY TEST  
RESULTS OF SHALE II JP-5 FUEL

JET FUEL THERMAL OXIDATION TEST						
Time (1) (weeks)	Test (2) Temperature, (°F)	Preheater Deposit Code	$\Delta P$ (mm Hg)	Total TDR	Maximum TDR	Peroxide (3) No. (MEQ)
25	520	1	1	24	2	0.310
	530	1	2	126	10	
	540	2	2	21	3	
	550	2	0	6	1	
	560	4P	>25	164	31	
26	520	+1	0	27	3	0.227
	540	4	0	164	20	
	550	+4	1	174	29	
31	500	-2	0	29	4	0.676
	540	4	1	140	17	
38	520	1	0	84	8	0.679
	530	+4P	0	86	17	
	540	4P	0	136	14	
44	510	+1	0	90	7	0.301
	520	3A	>25	0	0	
	520	3A	>25	0	0	
51	510	1	0	20	3	0
54	510	1	0	0	0	0.335
66	510	1	1	56	4	0.887
69	510	1	0	73	7	0.881
77	510	1	0	51	4	0.774
86	510	0	0	68	5	0.469
90	510	0	0	48	3	0.524
97	510	1	0	140	11	0.249
104	510	0	0	5	1	0.984

NOTES: (1) Fuel received at NAPC 7-17-79.

(2) MIL-T-5624L test temperature is 500°F; maximum allowable deposit code and  $\Delta P$  are 2 and 25 respectively.

(3) MIL-T-5624L peroxide limit is 1.0 MEQ.



TABLE VII  
LUBRICITY OF OIL SHALE II JP-5 FUEL SAMPLES

<u>Fuel</u>	<u>Wear Scar Diameter (WSD), mm</u>	
Oil Shale JP-5	0.48 0.48	0.48
+ 15 ppm Hitec E-515	0.37 0.40	0.39
+ 30 ppm Hitec E-515	0.35 0.37	0.36
+ 50 ppm Hitec E-515	0.34 0.33	0.34

TABLE VIII  
SINGLE TUBE HEAT EXCHANGER TEST CONDITIONS

	<u>Fuel</u>	<u>Lube</u>
Temperature, °C (°F)		
In	77 (170)	200 (400)
Out	174 (345)	174 (345)
Flow, liter/hr (GPH)	1.6 (0.42)	10.8 (2.86)

TABLE IXT63 LIGHT-OFF COMPARISON OF OIL SHALE II AND PETROLEUM DERIVED JP-5 FUELS

<u>Standard JP-5</u>		<u>Shale Derived JP-5</u>	
Start Time (sec)	Peak TOT, °C (°F)	Start Time (sec)	Peak TOT, °C (°F)
12.0	637 (1178)	12.8	640 (1184)
13.4	622 (1152)	11.8	641 (1186)
13.0	642 (1188)	12.0	647 (1196)
12.8 avg	634 (1173) avg	12.2 avg	643 (1189) avg

TABLE X  
GENERAL ELECTRIC  
LABORATORY FUEL ANALYSIS

<u>Test</u>	<u>Results</u>	
	<u>Petroleum</u> <u>JP-5</u>	<u>Oil Shale</u> <u>JP-5</u>
Distillation		
IBP, °F	365	343
10%, °F	383	359
20%, °F	393	377
30%, °F	402	385
40%, °F	413	393
50%, °F	419	399
60%, °F	429	407
70%, °F	438	413
80%, °F	446	422
90%, °F	463	443
End Point, °F	500	496
Loss, Vol. %	1.2	0.9
Residue, Vol. %	0.8	1.1
API Gravity	41.8	44.2
Aniline Gravity Product	5,692	5,834
Net Heat of Combustion, btu/lb	18,542	18,530
Flash Point, °F	150	148
Viscosity, cs @ 80°F	1.88	1.57
Viscosity, cs @ 100°F	1.55	1.31
Sediment	NIL	NIL

TABLE XITF34-GE-400 PERFORMANCE TEST RESULTSSTEADY STATE PERFORMANCE SUMMARY

	<u>Petroleum JP-5</u>	<u>Shale JP-5</u>
% FN marg @ max	-3.1	-3.1
% SFC marg @ 75% MC	-2.1	-1.5
NF margin @ Redline	-24	-16
NF @ 9275 FN	6,752	6,752

TRANSIENT PERFORMANCE STUDY

Average Burst Time (Idle-Max)	4.0 sec	4.0 sec
Average Chop Time (Max-Idle)	5.9 sec	5.7 sec
Average Bodie Time (Max-70%-Max)	9.6 sec	10.0 sec
Average Hot Restart Time	24.7 sec	24.0 sec
Average Cold Start Time	29.0 sec	28.0 sec

TABLE XIITF34-GE-400 COMBUSTOR FUEL SWIRLER POST TEST, FLOW CHECK RESULTS

<u>Swirler No.</u>	<u>Post Test Area</u>	<u>Percentage Blockage*</u>
1	0.137	1.2
2	0.135	2.6
3	0.130	6.6
4	0.139	0.3
5	0.130	6.6
6	0.136	2.4
7	0.138	0.7
8	0.139	-0.3
9	0.137	1.3
10	0.136	2.3
11	0.134	3.3
12	0.137	1.3
13	0.134	3.6
14	0.137	1.6
15	0.135	2.6
16	0.133	4.3
17	0.134	3.8
18	0.135	2.8

Average Post Time Area - .01353

Average Blockage - 2.622

\*Percent blockage based on drawing nominal effective area of 0.0139 sq. in.

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## 10. MERADCOM FUEL PROPERTY EVALUATIONS AND ENGINE TESTS

### Summary

The U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia (MERADCOM) manages and coordinates Army mobility fuels research and development. This section summarizes the results of evaluations of shale DFM, shale JP-5, and shale JP-8 carried out for MERADCOM by seven contractors: the Army Tank Automotive Command (TACOM), the Army Fuels and Lubricants Research Laboratory (AFLRL), Wayne State University, The University of Wisconsin, Cummins Engine Company, Inc., Avco-Lycoming Division, and Purdue University.

Table 10-1 lists the participants in the MERADCOM shale fuel evaluations, the work performed by each participant, and the references used in summarizing each evaluation. Four categories are represented: fuel property evaluations, short- and long-term engine performance tests, and a paper study on the use of shale fuels for Army generator sets.

The fuel property evaluations were performed by AFLRL. They conducted specification analyses on shale DFM, shale JP-5, and shale JP-8 and compared the results with the appropriate military specifications. The shale DFM and shale JP-8 met all specifications. The shale JP-5 failed two tests, smoke point and copper corrosion, by narrow margins.

AFLRL also tested shale fuels in five other important areas: storage stability, hydrocarbon type analysis, compatibility with petroleum fuels, additive response, and microbiological growth susceptibility. In terms of storage stability, the three shale distillates proved superior to JP-5 subjected to the same test. The results of the compatibility tests were also favorable. The additive response results were mixed: the shale fuels responded well to a cetane improver additive but rather poorly to a corrosion inhibiting additive package. The microbiological growth susceptibility tests revealed that both shale DFM and shale JP-5 support heavy growth of Cladosporium resinae.

Short-term engine performance tests were conducted on two gas turbine combustors (the Detroit Diesel Allison (DDA) T63 and Avco-Lycoming AGT 1500) and three diesel engines (the DDA 6V-53T and Teledyne-Continental AVDS-1790-2D and LDT-465-1C engines) that play important roles in the military fleet. In addition, fuel nitrogen conversion from petroleum-, shale-, and coal-derived fuels was evaluated in a high-speed J. I. Case diesel engine. Shale fuels were also tested in an adiabatic engine under development at Cummins Engine, Inc., that promises very broad fuel capabilities. Virtually all the short-term engine tests showed that suitably refined shale fuels can replace petroleum distillates with no significant deleterious effects on performance or reliability.



Long-term endurance tests burning shale DFM were performed in DDA 3-53, Cummins NTC-400 and Caterpillar 3208NA diesel engines. The tests ranged in length from 210 to 400 hours. Three techniques were employed to determine the effect of long-term operation with shale DFM: (1) full-power performance tests before and after the endurance test, (2) performance monitoring during the endurance test, and (3) disassembly and inspection for wear and deposits following testing. All three engines performed well on the shale DFM throughout the endurance tests. Post-test inspection revealed nothing to indicate that burning shale DFM would cause unusual maintenance problems in diesel engines.

An analysis of the use of shale-derived fuels in U.S. Army generator sets was performed by AFLRL. The analysis consisted largely of categorizing the generator sets currently in service and identifying the critical fuel properties for each type. The limited operating experience with shale fuels was reviewed to determine whether potential incompatibilities with Army generator sets could be identified. Shale fuels meeting the appropriate military specifications were judged to be generally acceptable for use in generator sets. However, fuel properties such as lubricity and hydrocarbon composition not covered by military specifications were seen as potential problem areas.

#### Fuel Property Evaluations

This section deals with fuel property evaluations performed by AFLRL. (10-1) Shale DFM, shale JP-5 and shale JP-8 were each tested for compliance with all appropriate military fuel specifications. In addition, several properties for which no precise specifications exist were also evaluated. These include storage stability, compatibility with petroleum derivatives and other properties that significantly impact the suitability of shale fuels for military applications.

#### Specification Analyses

Table 10-2 summarizes the specification properties of shale DFM, shale JP-5, and shale JP-8 as measured by AFLRL. The appropriate military specifications for each property are also included. Shale JP-8 met all requirements of MIL-T-83133A while the shale JP-5 met all except the smoke point and copper corrosion requirements of MIL-T-5624L. The smoke point value was low by 1.5 mm (17.5 versus 19). The copper corrosion test failure was thought to be due to the presence of a sulfur compound that can be removed during refining in the future.

The shale DFM met all specifications of the appropriate military standard, MIL-F-16884G. The cloud point of -14 C was erroneously reported in Ref. 10-1 as being 10 C; the actual measured value, however, is well below the maximum allowable -1 C.

### Storage Stability Tests

Storage stability tests were conducted by holding fuel samples at 43 C for 32 weeks. A JP-5 was evaluated concurrently with samples of shale DFM, shale JP-5 and shale JP-8. Specimens were extracted periodically and analyzed for gum content, dissolved oxygen and peroxide number.

Tables 10-3 and 10-4 summarize the results of the storage stability tests. Table 10-3 lists soluble and insoluble gum and precipitate levels for the three shale fuels and the petroleum JP-5 after 4, 8, 16, and 32 weeks at 43 C. The data are largely trendless, precluding a definitive comparison among the four samples. Nevertheless, it is clear that the storage stability of the three fuels is comparable to or better than that of the petroleum JP-5 in terms of gum and precipitate formation.

Table 10-4 presents dissolved oxygen and peroxide number readings for the shale fuels only at zero, 4, 8, 16, and 32 weeks. Dissolved oxygen readings show a gradual decrease with time, while peroxide number exhibits the opposite trend. The presence of peroxide in distillate fuels is of concern because of the potential for attack on elastomeric compounds used for O-rings and gaskets. Peroxide levels in all three fuels became appreciable sometime after the fourth week of storage. Peroxide formation in shale DFM was significantly greater than in shale JP-5 or shale JP-8.

### Hydrocarbon Type Analyses

The hydrocarbon type compositions of shale DFM, shale JP-5, and shale JP-8 were determined by AFLRL using four separate techniques: fluorescent indicator absorption (FIA), proton nuclear magnetic resonance (proton NMR), natural abundance carbon-13 nuclear magnetic resonance ( $^{13}\text{C}$  NMR), and aromatic carbon by ultraviolet spectrometry. The techniques have relative strengths and weaknesses that are functions of fuel type and were not expected to give identical results. The proton NMR and  $^{13}\text{C}$  NMR tests were repeated on fuel samples that had undergone the 32-week storage stability test to determine whether any significant change had taken place in the hydrocarbon types of the three shale derivatives.

Table 10-5 summarizes the results of the hydrocarbon type analyses. The FIA technique yielded aromatic content readings significantly greater than those of the other techniques, particularly for the shale DFM. The aromatic contents of the shale fuels were not changed appreciably after storage for 32 weeks at 43 C. The ultraviolet technique, which distinguishes among single-, double- and triple-ring aromatic species, revealed that the shale DFM has a significant amount of double-ring aromatics (4.03 percent by weight).

### Compatibility With Petroleum Fuels

Storage stability tests were employed to investigate the compatibility of shale fuels with petroleum fuels. Blends of shale JP-5 and petroleum JP-5, and of shale DFM and petroleum diesel fuel were tested by two procedures: (1) holding the fuels at 150 C for 1.5 hours and evaluating the amount of insoluble residue formed, and (2) holding the samples at 80 C for up to 14 days and evaluating gum formation. The shale and petroleum fuels were tested in neat form and as 50/50 blends in both series of experiments.

Tables 10-6 and 10-7 present the results of the high-temperature stability tests for the JP-5 and diesel fuels, respectively. Several techniques were employed to evaluate the amount of residue formed, including visual and gravimetric determinations and a steam jet gum procedure.

When filterable particulates are used as the criterion, no compatibility problems are apparent between the shale and petroleum derivatives. The levels of particulates formed in the blends are about midway between the levels formed in the neat specimens. Both shale DFM and shale JP-5 formed less particulates than their petroleum counterparts.

The steam jet gum measurements for the blended fuels exceeded those for the neat fuels in both the JP-5 and diesel fuel experiments. This observation may indicate a synergism between the shale and petroleum products during oxidation reactions under these conditions.

In the 80 C storage stability experiments, the blended fuels exhibited stability comparable to or slightly better than the neat petroleum fuels. In contrast to the high-temperature experiments, the neat shale fuels were much less stable than the blends or the neat petroleum fuels. The authors conclude that the shale-derived fuels oxidize more rapidly at 80 C than at 150 C or at 43 C, as indicated in the shale fuel storage stability tests discussed previously.

### Additive Response

The additive responses of shale DFM, shale JP-5, and shale JP-8 were investigated in two areas: cetane number improvement and corrosion inhibition. In each case, the shale fuels were treated with additives prepared for petroleum fuels and the impact on the appropriate property was measured.

Figure 10-1 illustrates the effect of a cetane improver on the cetane numbers of shale DFM, shale JP-5, and shale JP-8. The petroleum fuel curve for Figure 10-1 is based on data supplied by the additive manufacturer. The responses of the shale fuels are essentially comparable to that of the petroleum fuel.

Table 10-8 summarizes the corrosion tendencies of the shale fuels. In neat form, none of the fuels is particularly effective at inhibiting corrosion. Unfortunately, the addition of a corrosion inhibiting additive improved the performance of the shale JP-5 and shale DFM only slightly and the JP-8 not at all. The "C" rating achieved by the shale JP-8 indicates that it is not acceptable for pipeline operation. The shale DFM and shale JP-5 were acceptable only after treatment with the additive.

#### Microbiological Growth Susceptibility

The susceptibility to microbiological growth of shale DFM and shale JP-5 was investigated by inoculating a mixture of fuel and nutrient medium with Cladosporium resinae. The mixture was incubated in a screw-cap test tube at 30 C for 6 months and observed periodically for growth.

Table 10-9 presents the growth ratings observed at regular intervals during the test. Growth was rated as "good" after 30 days and "heavy" at each interval thereafter. No comparative data for petroleum fuels are reported.

#### Short-Term Performance Tests

This section summarizes short-term diesel engine and gas turbine combustor tests performed by AFLRL, the University of Wisconsin, Cummins Engine Company, Inc., Avco-Lycoming Division, and Purdue University. In addition, diesel fuel injector studies performed at Wayne State University are also discussed.

#### Engine Descriptions

Table 10-10 presents the specifications of the diesel engines tested. Two of these devices were actually single cylinders of multi-cylinder engines; the other three were full production engines. All five were turbocharged. Two gas turbine combustors, a DDA T-63 and an Avco-Lycoming AGT 1500, were also tested. Each of these devices is described briefly below.

The Detroit Diesel/Allison Division 6V-53T is a 6-cylinder, 2-stroke-cycle engine with a displacement of 318 cubic inches. The cylinders are arranged in a 60 degree V configuration. The engine delivers 300 hp at its rated speed of 2800 rpm. The engine is described by AFLRL as being rather fuel sensitive<sup>(10-1)</sup>. The 6V-53T powers the M551 tank and the M113 family of armored carriers.

The Teledyne Continental LDT-465-1C uses the M.A.N. combustion system to achieve multifuel capability(10-1). The obvious advantage of multifuel capability makes this the highest density engine design in the army fleet. The LDT-465-1C is a 6-cylinder, 4-stroke engine that displaces 478 cubic inches and delivers 140 hp at 2600 rpm. The engine will operate on fuels ranging from low-octane gasoline to distillate fuels and will start and attain full power on fuels with cetane numbers as low as 20.

The Teledyne Continental AVDS-1790-2D is an air-cooled 12-cylinder engine. This engine powers the M60 main battle tank and is therefore vitally important to the military(10-1). A single cylinder from an AVDS-1790-2D was mounted on a CUE crankcase for testing purposes. Turbocharger operation was simulated by placing a back-pressure valve in the exhaust duct and supplying combustion air at elevated temperature and pressure.

The J. I. Case engine tested at the University of Wisconsin is a 4-cylinder, 4-stroke device that displaces 336 cubic inches(10-3). The fuel supply system was configured such that fuels of varying nitrogen content could be fed to the engine simply by turning a three-way valve, making possible a direct evaluation of NO<sub>x</sub> formation as a function of fuel nitrogen content.

The Cummins NTC-400 engine is a 6-cylinder, 4-stroke device used commercially for over-the-road vehicles. A single cylinder mock-up was tested in three different configurations: conventional, uncooled, and adiabatic(10-4). The uncooled and adiabatic configurations employed cylinder liners and piston heads made of high-temperature-resistant materials. Because the combustion chamber operates at higher temperatures, these configurations are thought to offer the potential for broader fuel capability than conventional diesel engines.

The Allison T-63 gas turbine is used in several U.S. Army helicopters. A combustor from this engine was evaluated by AFLRL(10-1). The combustor is a single-can type employing pressure atomization. Ignition is by a repetitive-spark igniter located adjacent to the atomizer.

The AGT 1500 gas turbine engine powers the Army's new M-1 tank(10-6). The combustor was developed to use a variety of conventional fuels and is currently authorized to operate on various diesel fuels and JP-4 and JP-5. The engine has also been tested on gasoline and residual fuel oil.

### Procedures and Results

The methods employed and the results achieved in the various short-term performance tests are presented in this section. Because of the similarity of the procedures followed in the short-term tests and the conclusions drawn from the results, only brief descriptions are included herein.

Short-term tests of AFLRL were performed on three diesel engines: the DDA 6V-53T, the Teledyne-Continental LDT-465-1C, and a single-cylinder version of the Teledyne-Continental AVDS-1790-2D(10-1). The engines were assembled to manufacturers' specifications and mounted on dynamometers. The engines were operated on shale DFM and shale JP-5 as well as DF-2 diesel fuel. Maximum power output and brake-specific fuel consumption were measured for each fuel and each engine at a variety of rotational speeds. The results were reported as percent change in power output and fuel consumption for the two shale and relative to the results achieved with the DF-2. Due to a shortage of fuel, the LDT-465-1C was not evaluated sufficiently with shale JP-5 to draw any substantive conclusions.

Table 10-11 summarizes the results achieved in short-term diesel engine tests at AFLRL. The table includes the percent change in power output and fuel consumption for each engine as the result of switching from DF-2 to shale DFM and shale JP-5. The entries represent averages of the values recorded at a variety of rotational speeds for each engine.

All three engines performed satisfactorily on the shale fuels. The DDA 6V-53T proved to be the most fuel sensitive of the group, as expected. This engine experienced a decrease in power output and an increase in fuel consumption with both shale fuels relative to DF-2. The effect was more pronounced with shale JP-5 than with shale DFM. The results were largely attributed to the differences in heats of combustion of the three fuels.

The AVDS-1790-2D demonstrated improved performance with shale DFM relative to DF-2. Performance was worse with shale JP-5 than with DF-2. The differences were slight in all cases, ranging from 2.1 to 3.2 percent. The LDT-465-1C exhibited even less fuel sensitivity when switching from the DF-2 to shale DFM, as one might expect based on its multifuel design.

A complimentary study on the fuel injection system of the LDT-465-1C was performed at Wayne State University(10-2). The study consisted of measuring fuel properties relevant to injector performance for six candidate fuels, including shale DFM and five petroleum fuels. Each fuel was then pumped through the injector system to determine the sensitivity to fuel type of various measures of injector performance.

Table 10-12 summarizes the properties measured for the shale DFM and DF-2. Each property was evaluated according to an established ASTM procedure, where applicable. Distillation curves were also prepared and were essentially identical to the values presented in Table 10-2 for the shale DFM.

The performance of the fuel injector with shale DFM was not significantly different from its performance with DF-2. This result is not surprising in view of the similar densities and viscosities of the two fuels.

A study of fuel nitrogen conversion to  $\text{NO}_x$  in a diesel engine was performed at the University of Wisconsin(10-3). Four fuels were evaluated: (1) a DF-2 diesel fuel, (2) shale DFM, (3) a mixture of coal-derived SRC-II and Phillips Petroleum T-17, a high-cetane additive, and (4) the DF-2 fuel doped with pyridine to increase its nitrogen content.

The fuels were burned in a 4-cylinder J. I. Case diesel engine. The fuel system was configured in such a way that either of two fuels could be selected by turning a three-way valve. This made possible direct comparisons between the test fuels and the DF-2 without concern for changes in engine settings or ambient conditions. Tests were conducted at a variety of engine rotational speeds and loads. Variables measured in addition to  $\text{NO}_x$  levels were brake horsepower, fuel consumption, smoke level and CO and hydrocarbon emissions.

Table 10-13 presents a comparison of the  $\text{NO}_x$  emissions achieved with the test fuels to those with DF-2. The fuel nitrogen and aromatic contents are also presented. The relative  $\text{NO}_x$  emissions presented in the table represent average values from 12 test conditions for the shale and pyridine-doped test fuels and 20 test conditions for the SRC-II blend.

The shale DFM produced the lowest  $\text{NO}_x$  emissions of any of the fuels tested, in spite of nitrogen and aromatic contents essentially identical to those of the DF-2. The SRC-II blend nitrogen content was roughly 17 times as great as that of the DF-2. However, the  $\text{NO}_x$  emissions when burning the blend were only 3.6 percent greater than those when burning the DF-2. The aromatic content of the blend was also significantly higher than that of the DF-2. The pyridine-doped fuel had 50 times as much nitrogen as the DF-2 as well as a higher aromatic content; nevertheless, the  $\text{NO}_x$  emissions with this fuel were virtually identical to those with the DF-2. Thus, this study demonstrated no clear correlation between  $\text{NO}_x$  emissions and either fuel nitrogen or aromatic content.

Other measures of engine performance were also quite satisfactory when burning shale DFM. Power output, fuel consumption, and smoke emissions were essentially identical to the values recorded for DF-2. Hydrocarbon emissions were substantially lower with shale DFM.

The Cummins Engine Company, Columbus, Indiana, is developing diesel engines incorporating ceramic parts to eliminate engine cooling, under DOE and TACOM sponsorship. The primary object of the work reported here was to determine the capability of the uncooled engines, with their high in-cylinder temperatures, to burn poor-quality, low-cetane fuels<sup>(10-4)</sup>. As part of this work, engine operating and emission characteristics with shale DFM and shale JP-5 were compared with those with DF-2.

Figure 10-2 shows a cross-sectional view of the single-cylinder test engine. The engine, based on the Cummins NTC-400, was tested in three configurations: (1) a conventional water-cooled design, (2) an uncooled design in which the original pistons, cylinder liners and piston rings were replaced with high-temperature-resistant metal components, and (3) an adiabatic configuration in which ceramic linings were installed on the piston and cylinder heads and two of the three piston rings were ceramic-coated.

The five fuels tested in the engine were shale DFM, shale JP-5, two coal liquids, and a petroleum DF-2. Each engine configuration was operated at three fuel injection timings over the standard 13-mode federal emissions cycle. Fuel consumption and  $\text{NO}_x$ , hydrocarbon, and particulate emissions were monitored. Particulates were evaluated for biological mutagenicity using the Ames bioassay technique.

Figure 10-3 presents brake-specific fuel consumption curves for shale DFM and the DF-2 in the cooled engine at the most advanced injection timing. The trend exhibited in Figure 10-3 is representative of the results achieved in all three engine configurations in that the fuel consumption while burning shale DFM was generally slightly less than that with the DF-2. Shale JP-5 was burned only in the cooled engine and yielded fuel consumption results essentially identical to those for shale DFM.

Likewise, emissions and particulate mutagenicities exhibited by the DF-2 and shale DFM were similar. Differences between the two fuels were often negligible; significant differences were frequently trendless and therefore largely unexplainable. The results revealed nothing that would limit the use of shale DFM or shale JP-5 as a replacement for the DF-2 under the conditions tested.

Shale DFM, shale JP-5 and Jet A fuel were burned in an Allison T-63 gas turbine combustor by AFLRL.<sup>(10-1)</sup> Tests were conducted at six fuel settings ranging from 10 to 100 percent of full power. The fuels were compared on the basis of combustion efficiency, flame radiation and emissions of  $\text{NO}_x$ , CO, hydrocarbons and smoke.

Table 10-14 summarizes the results achieved with the Allison T-63 combustor. In general, the combustion properties of the shale DFM and shale JP-5 did not differ significantly from those of the Jet A



fuel. Higher smoke levels and flame radiation readings exhibited by the shale fuels are attributable to their lower hydrogen contents as compared to the Jet A fuel.

Additional testing of shale DFM and shale JP-5 in gas turbine combustors was performed at Avco-Lycoming Division(10-6) and Purdue University (10-7). The Avco-Lycoming tests were performed in an actual AGT 1500 gas turbine combustor, while the Purdue tests were conducted in a geometrically simple test combustor under conditions typical of AGT 1500 operation. The objective of both projects was to determine the sensitivity to fuel type of this critically important engine, which powers the Army's M-1 tank. Avco-Lycoming burned shale DFM, shale JP-5 and DF-2 in their AGT 1500 combustor. The Purdue tests included seven fuels: unleaded gasoline, DF-2, No. 4 and No. 6 residuals, shale DFM, shale JP-5 and a petroleum-derived JP-10, which is a high density ramjet fuel.

Both projects studied the influence of fuel type on ignition, blowout, thermal efficiency, smoke formation and gaseous emissions. Avco-Lycoming also reports results on droplet spray characterization, combustor wall temperatures and exit-plane gas temperature distribution. Researchers at Purdue University measured radiation intensities at several locations on the combustor wall and probed internally for gaseous species and soot.

Table 10-15 presents idle performance data recorded at Avco-Lycoming for shale DFM, shale JP-5 and DF-2. Combustion efficiency,  $\text{NO}_x$  and smoke emissions, and temperature variance ratio (a measure of the consistency of exit-plane gas temperatures) are included. Also presented are the contributions of CO and unburned hydrocarbon emissions to combustion inefficiency. In nearly all categories, the shale fuels outperformed the DF-2. Generally speaking, the effects of fuel type on combustor performance were very slight, indicating that the shale fuels are acceptable substitutes for the DF-2 in this combustor. Ambient temperature variations, which ranged from 0 to 125 F during testing, had a more pronounced effect on combustor performance than did fuel type.

These observations were reinforced by the results achieved at Purdue University. Most performance measures were largely insensitive to fuel type; those variations that did occur (e.g., wall radiation levels) were generally attributable to variations in fuel hydrogen content. The authors concluded that "...shale-derived fuels manufactured to specification can be expected to perform similarly to petroleum derived fuels of the same specification in terms of soot, radiation, efficiency and probably ignition."(10-7)

### Long-Term Endurance Tests

This section describes experiments in which commercial diesel engines were operated for hundreds of hours on shale DFM. The tests were performed at the U.S. Army Tank/Automotive Command (TACOM) in Warren, Michigan<sup>(10-8,9)</sup> and at the Army Fuels and Lubricants Research Laboratory (AFLRL) in San Antonio, Texas.<sup>(10-1)</sup> The three engines tested were the Cummins NTC-400, the Caterpillar 3208NA and the Detroit Diesel 3-53. The objective was to verify that production diesel engines would operate satisfactorily and without unusual wear on shale DFM. The project completed at TACOM also included tests with shale JP-5 and a petroleum DF-2 to reveal any variations in engine performance due to fuel type.

### Engine and Facility Descriptions

Table 10-16 provides the specifications of the three engines tested. All are standard production models of commercially proven medium-duty diesels. The Cummins NTC-400 develops roughly twice the horsepower of the Caterpillar 3208NA by virtue of turbocharging and a larger displacement. The Detroit Diesel Allison 3-53 is a 3-cylinder engine of substantially lower displacement and power output and is used in the military's M561 1 1/4-ton vehicle.

Testing of the two larger engines took place in an engine test cell at TACOM. The engines were mounted on dynamometers and were extensively instrumented to measure fuel flow rate, shaft torque, rotational speed and various temperatures and pressures. Exhaust smoke density was measured with a Bosch model EFAW-68A smoke meter. No other emissions measurements were made.

The DDA 3-53 engine was tested at AFLRL, located at Southwest Research Institute. The test equipment was similar to that employed at TACOM with the exception that smoke data were not reported by AFLRL.

### Procedures and Results

TACOM Tests. Following a breaking-in period, each engine was tested at full load over a range of rotational speeds with three fuels: shale DFM, shale JP-5 and DF-2. Fuel consumption, shaft torque and brake horsepower were recorded at each rotational speed.

Each engine was subjected to a 400-hour endurance test following the full-load evaluations. The objective was to reveal any operational or maintenance difficulties caused by long-term operation on shale DFM. Smoke readings and full-load performance data were recorded periodically during the endurance test.

Table 10-17 summarizes the 5-hour pattern of rotational speeds and loads followed during the test. This so-called NATO Standard Cycle was repeated eighty times for each engine. Lube oil consumption and composition and crankcase pressure were monitored throughout the tests to detect any detrimental fuel impacts on lubrication.

Following the endurance tests, full-load performance evaluations identical to those completed prior to the endurance tests were conducted. Any significant differences in the results achieved before and after the endurance tests would suggest that long-term operation on shale DFM was responsible. The engines were disassembled and inspected for deposits and wear at the completion of testing.

Tables 10-18 and 10-19 present the full-power performance before and after the endurance tests for the Cummins NTC-400 and the Caterpillar 3208NA, respectively. The quantities listed are maximum power and torque and minimum fuel consumption and the rotational speeds at which the maxima and minima occurred. Differences in the results achieved before and after the endurance tests are generally slight and largely random, probably reflecting experimental uncertainty. The most sizable change was a 10 percent increase in power achieved by the Caterpillar 3208NA while burning shale JP-5. In contrast, the Cummins NTC-400 experienced a 3 percent decrease in power with the same fuel. Taken as a whole, the results indicated that neither engine experienced any deleterious effects attributable to the 400-hour test on shale DFM.

Table 10-18 and 10-19 also afford a direct comparison of engine performance as a function of fuel type. The results achieved with the DF-2 and shale DFM are essentially identical. Shale JP-5, on the other hand, produced lower power and torque but at improved fuel economy relative to the other two fuels.

Observations made during the endurance tests also indicated that shale DFM is an acceptable fuel. Neither engine experienced a failure or any anomalous behavior whatsoever that could be attributed to the fuel. Performance data recorded at 100-hour intervals were consistent with the pre-test values. Oil consumption and crankcase pressures were completely acceptable.

Tables 10-20 and 10-21 summarize the smoke meter readings recorded for the Cummins NTC-400 and Caterpillar 3208NA, respectively. Data for both the left and right exhaust manifolds of the V-8 Caterpillar engine are included. No trends in smoke level with time are apparent for either engine; likewise, no correlation between smoke level and fuel type is discernible. The NATO standard for smoke level, a maximum reading of 4.5, was exceeded only once during the endurance tests (a reading of 4.6 at 1200 rpm after 100 hours with the Caterpillar 3208NA).

Disassembly and inspection of the engines following testing revealed no abnormal deposits or wear attributable to the fuel. The

Caterpillar 3208NA was virtually deposit-free, while the Cummins NTC-400 had minor deposits on pistons and cylinder heads. Wear parts on both engines were measured and found to be within manufacturer's specifications.

AFLRL Test. Prior to endurance testing, the Detroit Diesel Allison 3-53 engine was subjected to full-load testing at seven rotational speeds while burning shale DFM. Torque, power output and fuel consumption were recorded. The tests were repeated after the 210-hour endurance test to check for significant changes in engine performance.

The endurance test was conducted according to the U.S. Army/CRC wheeled-vehicle operating cycle. Power output, torque, fuel consumption and various temperatures and pressures were recorded at regular intervals. Lubricant physical properties and contamination with wear metals were also monitored closely. Following the completion of testing, the engine was disassembled and inspected for objectionable wear and deposits. A similar test conducted previously with DF-2 provided a basis for comparison.

Figure 10-4 presents full-power performance data recorded before and after the 210-hour endurance test with the Detroit Diesel Allison 3-53 engine. The figure includes data on fuel consumption, power output and shaft torque as functions of rotational speed. The engine was burning shale DFM during these tests as well as the endurance test. In spite of a certain amount of scatter in the data, the results clearly suggest that the engine suffered no deleterious effects due to its long exposure to shale DFM. A similar test performed previously with DF-2 yielded nearly identical results.

The positive results achieved in full-power testing are supported by other observations made in the test program. Lubricating oil consumption and wear metals contamination readings were normal throughout the endurance test. Disassembly and inspection at the completion of testing revealed only inconsequential deposits and no significant wear or other signs of component distress.

#### Shale Fuels for Army Generator Sets

A study of the use of shale fuels in Army generator sets was performed by AFLRL.(10-19) The objective was to investigate the feasibility of operating Army generator sets on shale fuels and to recommend test procedures for operational verification. Generator sets powered by gasoline, diesel and gas turbine engines were included in the survey. The critical fuel properties for each type were identified. The limited operating experience accumulated to date with shale fuels was then reviewed to determine whether the shale fuel properties were likely to prove satisfactory. No fuel or engine experimental evaluations were undertaken as part of this study.

### Procedure

A thorough survey of the generator sets currently used by the Army was prepared by AFLRL. Manufacturers and model numbers were identified, as well as the engine and fuel type, generator frequency and electrical power output. Groupings were established on the basis of similarity of design on the premise that engines of roughly equivalent configuration would be expected to respond in like fashion to shale fuels.

The issue of fuel/engine compatibility was addressed by identifying the critical fuel properties for gasoline, diesel and gas turbine engines. Laboratory analyses of shale-derived gasoline, diesel and jet fuels were then examined in light of these critical properties. The results of performance tests of shale fuels in commercial and military engines were also reviewed in terms of combustion characteristics, deposits and fluid handling qualities. Engine manufacturers were interviewed for their opinions on the use of shale fuels in their products and to determine whether they had experience with shale fuels that was not reported in the literature. Non-specification properties and issues such as lubricity and materials compatibility were also addressed.

### Results and Recommendations

A total of 197 generator sets supplied by 21 manufacturers was evaluated in the survey. Of this total, 77 are gasoline-powered, 108 are diesel-powered and 12 are driven by gas turbines. Appendices A through D of Ref. 10-10 list the generator sets according to various designations.

Tables 10-22, 23 and 24 list the fuel properties identified by AFLRL as being of concern for gasoline, diesel and gas turbine engines. For each fuel property, the area of concern and a potential resolution are included. In most cases, the resolution consists of controlling the property by specification, implying that shale fuels refined to the same standards as petroleum fuels should provide acceptable service in Army generator sets.

Two properties not directly covered by military specifications that are cited as being of concern by AFLRL are lubricity and naphthene content. Low lubricity causes rapid wear in fuel injectors and pumps and other devices that depend upon the fuel itself for lubrication. High naphthene content causes elastomer degradation that may result in catastrophic failure or decreased engine life. AFLRL recommends that these properties be routinely evaluated in fuels to be used for generator sets.

The case studies of engines operated on shale fuels presented by AFLRL revealed no consistent trends that would indicate

incompatibilities with Army generator sets. The author concludes that the performance of shale fuels was essentially comparable to that of petroleum fuels and that refiners should be able to provide shale fuels suitable for generator set operation. Nevertheless, shale fuel evaluations in two gas turbine and six diesel engines are recommended to verify that such fuels are acceptable for use in Army generator sets. No gasoline engine tests were recommended due to the present unavailability of shale-derived gasoline for testing.

### Conclusions

The U.S. Army Mobility Equipment Research and Development Command (MERADCOM) sponsored a broad series of experiments to evaluate the use of shale-derived DFM, JP-5 and JP-8 in military engines. The experiments included fuel property evaluations, short-term engine performance tests and long-term engine endurance tests. A paper study on the use of shale fuels in Army generator sets was also completed.

The conclusions derived from these numerous independent studies were highly uniform. The shale fuels were found to be of high quality, often higher than that of petroleum fuels against which they were evaluated. The performance of engines operated on the shale fuels was very good in all cases. Differences in engine performance while burning shale fuels versus petroleum derivatives were generally attributable to property variations between the fuels. Taken as a group, the results of these studies indicate that suitably refined shale fuels are completely acceptable for use in military engines similar to those evaluated.

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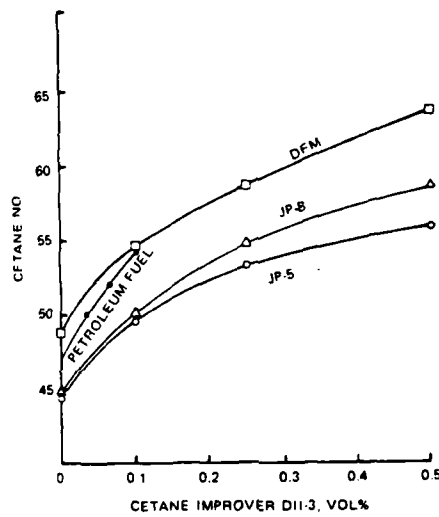


FIGURE 10-1. EFFECT OF CETANE IMPROVER ADDITIVE  
ON SHALE-DERIVED FUELS<sup>(10-1)</sup>



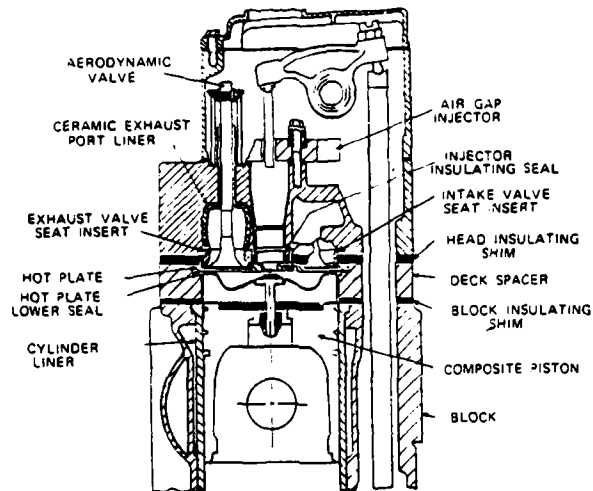


FIGURE 10-2. CROSS SECTION OF CUMMINS SINGLE-CYLINDER  
ADIABATIC DIESEL ENGINE (10-5)

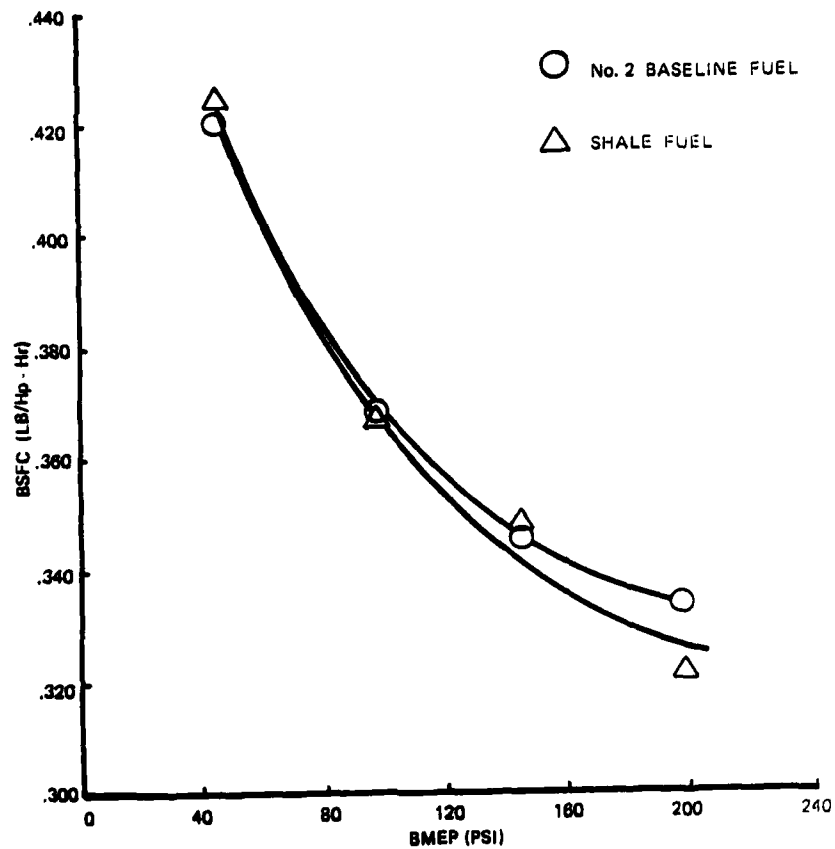


FIGURE 10-3. BRAKE-SPECIFIC FUEL CONSUMPTIONS FOR SHALE DFM AND  
DF-2 AT 1900 RPM, INJECTION TIMING 27° BEFORE TOP DEAD CENTER (10-4)

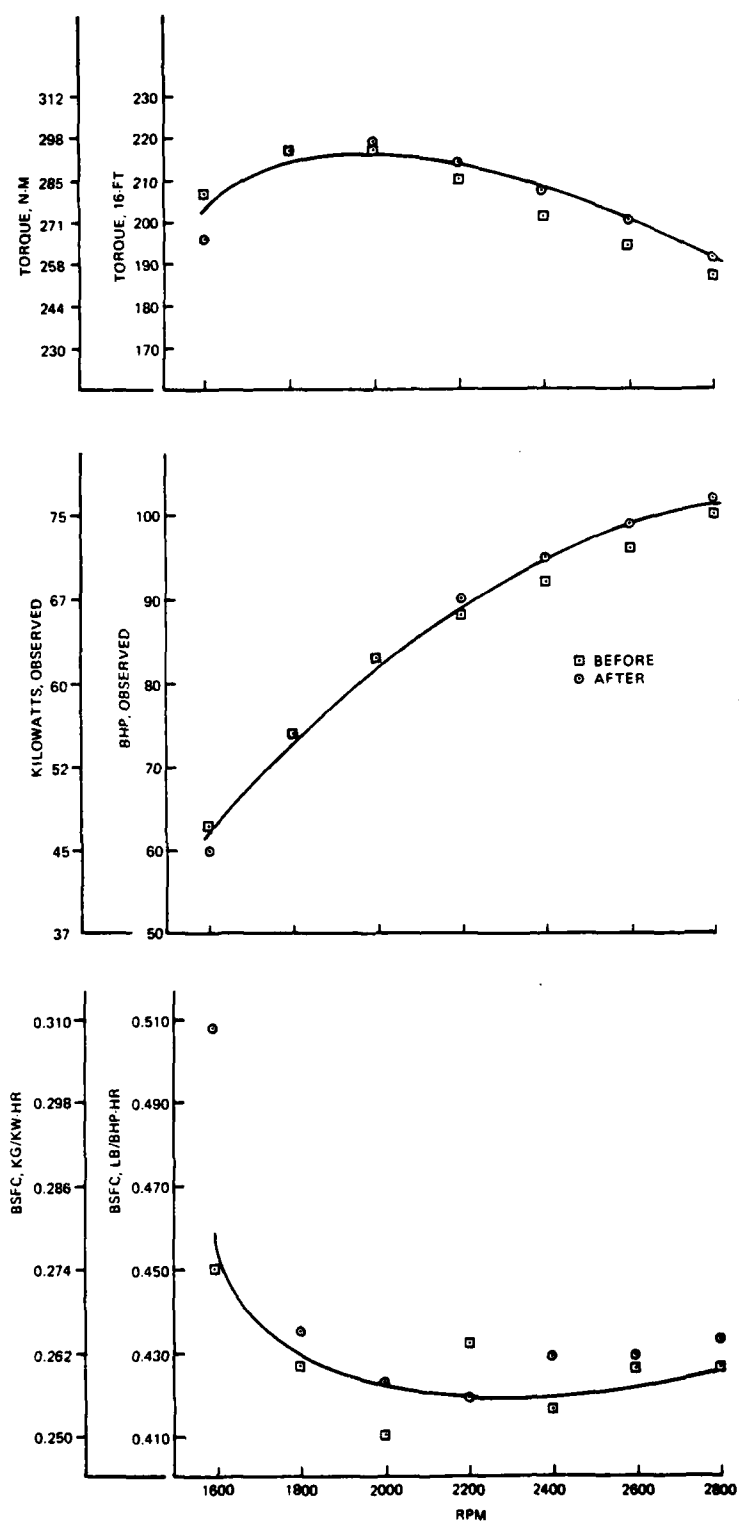


FIGURE 10-4. PERFORMANCE OF DETROIT DIESEL 3-53 ENGINE BEFORE AND AFTER  
210-HOUR ENDURANCE TEST BURNING SHALE DFM<sup>(10-1)</sup>

TABLE 10-1. PARTICIPANTS IN MERADCOM SHALE FUEL EVALUATIONS

<u>Subject</u>	<u>Participant</u>	<u>Reference</u>
Fuel Property Evaluations	AFLRL	10-1
Short-Term Performance Tests		
DDA 6V-53T Diesel Engine Test	AFLRL	10-1
Teledyne-Continental AVDS-1790-2D Diesel Engine Test*	AFLRL	10-1
LDT-465-1C Multifuel Engine Test	AFLRL	10-1
LDT-465-1C Injector Studies	Wayne State University	10-2
Fuel-Nitrogen Conversion in J. I. Case Diesel Engine	University of Wisconsin	10-3
Cummins Adiabatic Diesel Engine Test	Cummins Engine Company, Inc.	10-4,5
DDA T63 Combustor Rig Test	AFLRL	10-6
AGT-1500 Gas Turbine Combustor Tests	Avco-Lycoming Division Purdue University	10-7
Long-Term Endurance Tests		
DDA 3-53 Diesel Engine	AFLRL	10-1
Cummins NTC-400 Diesel Engine	U. S. Army TACOM	10-8
Caterpillar 3208NA Diesel Engine	U. S. Army TACOM	10-9
Shale Fuels for Army Generator Sets	AFLRL	10-10

\* Single cylinder adapted to a CUE crankcase

TABLE 10-2. FUEL PROPERTIES MEASURED BY AFLRL AND CORRESPONDING  
MILITARY SPECIFICATIONS (10-1)

Properties	Shale JP-8	JP-8 Requirements	Shale JP-5	JP-5 Requirements	Shale DFM	DFM Requirements
Specific Gravity, 15.6/15.6°C	0.8044	0.775-0.840	0.8081	0.788-0.845	0.8353	---
Gravity, °API	44.4	37-51	43.6	36-48	37.9	Record
Distillation, °C						
IBP	178	---	179	---	206	---
10% Recovered	187	205 max	189	205 max	233	---
20% Recovered	189	---	192	---	243	---
50% Recovered	201	---	202	---	264	---
90% Recovered	227	---	228	---	295	357 max
End Point	257	300 max	248	290 max	312	385 max
% Recovered	98.5	---	98.5	---	99	---
% Residue	1.0	1.5 max	1.5	1.5 max	1	3 max
% Loss	0.5	1.5 max	0	1.5 max	0	---
Flash Point, °C	57	38 min	62	60 min	80	60 min
Viscosity at 37.8°C, cSt	1.30	---	1.38	---	2.71	1.8-4.5
Viscosity at -20°C, cSt	4.19	8.0 max	4.68	8.5 max	---	---
Aniline Point, °C	62.4	---	60.4	---	67.0	Record
Cloud Point, °C	---	---	---	---	-14	-1 max
Pour Point, °C	---	---	---	---	-18	-7 max
Freezing Point, °C	-52	-50 max	-51	-46 max	---	---
Existent Gum, mg/100ml	0.4	7 max	0	7 max	0	---
Total Acid Number, mg KOH/g	0.01	0.015 max	0	0.015 max	0.001	0.3 max
Neutrality	---	---	---	---	Neutral	Neutral
Aromatics, vol% (FIA)	21	25 max	22	25 max	30	---
Olefins, vol% (FIA)	2	5 max	2	5 max	1	---
Carbon, wt%	86.05	---	85.92	---	86.54	---
Hydrogen, wt%	13.70	13.5 min	13.68	13.5 min	13.36	---
Nitrogen, ppm	0.31	---	<1	---	<1	---
Oxygen, wt%	0.40	---	0.38	---	0.37	---
Sulfur, wt%	0.002	0.30 max	0.005	0.40 max	0.004	1.00 max
Thermal Oxidation Stability (JTOT) at 260°C						
ΔP, mm Hg	0	25 max	0	25 max	0	---
Tube rating, visual	2	<3	1	<3	3	---
TDR-spun	10.0	---	2.0	---	11.5	---
TDR-spot	12.0	---	8.0	---	19	---
Cu Corrosion at 100°C	1A	1B max	2C	1B max	1A	1 max
Net Heat of Combustion, MJ/kg	42.82	42.8 min	42.68	42.6 min	42.50	---
Smoke Point, mm	20.2	19 min	17.5	19 min	16.5	---
Aniline-Gravity Product	6,407	---	6,134	4,500 min	---	---
Visual Appearance	Straw, clear	---	White, clear	---	White, clear	Clear, bright
Color, ASTM Rating	0.5	---	<0.5	---	<0.5	3 max
Accelerated Stability, mg/100 ml	0.29	---	0.14	---	0.20	2.5 max
Particulate Matter, mg/l	0.3	1 max	0.1	1 max	0.5	8 max
Ash, wt%	---	---	---	---	0	0.005 max
Cetane Number	45	---	45	---	49	45 min
Carbon Residue on 10% bottoms, wt%	---	---	---	---	0.04	0.2 max
Demulsification, minutes	---	---	---	---	5	10 max
Ring Carbon						
Mono-aromatics, wt%	13.84	---	13.54	---	11.58	---
Di-aromatics, wt%	1.19	---	1.36	---	4.03	---
Tri-aromatics, wt%	0.003	---	0.002	---	0.045	---
GC Distillation, °C						
0.1 wt% off	120.1	---	136.5	---	103.4	---
1 wt% off	153.6	---	159.7	---	152.3	---
10 wt% off	170.4	186 max	174.5	185 max	214.0	---
20 wt% off	176.6	---	185.3	---	236.2	---
50 wt% off	203.1	---	208.9	---	271.8	---
90 wt% off	241.0	---	245.9	---	316.5	---
95 wt% off	252.2	---	255.0	---	323.3	---
99 wt% off	274.6	---	278.8	---	336.1	---
99.5 wt% off	285.7	330 max	291.6	320 max	342.1	---
HPLC Aromatics, wt%	23.5	---	24.9	---	27.8	---
HPLC Saturates, wt%	76.5	---	75.1	---	72.2	---

TABLE 10-3. GUM AND PRECIPITATE LEVELS FOLLOWING STORAGE AT 43 C,  
MG/100 ML(10-1)

mg/100 ml								
Code No.	Description	Initial	4 Weeks			8 Weeks		
			Soluble gum	Insoluble gum	Precipitate	Soluble gum	Insoluble gum	Precipitate
AL-8466-T	JP-8 from Paraho-II Shale Oil	0.4	A-1.2* B-1.2*	0.7	0.1	A-0.9 B-0.9	0.6	0.1
AL-8436-T	JP-5 from Paraho-II Shale Oil	0	A-0 B-0	0.5	0.1	A-0 B-0	0.4	0.1
AL-8437-T	DFM from Paraho-II Shale Oil	0	A-0 B-0	0.6	0.6	A-0.6 B-0.5	0.9	1.0
AL-6400-T	Petroleum-Based JP-5	0.3	0.6	1.4	0.1	1.7	0.5	0

Code No.	Description	16 Weeks			32 Weeks		
		Soluble gum	Insoluble gum	Precipitate	Soluble gum	Insoluble gum	Precipitate
AL-8466-T	JP-8 from Paraho-II Shale Oil	A-1.1 B-1.0	1.0	0.2	A-1.7 B-1.7	2.3	0.3
AL-8436-T	JP-5 from Paraho-II Shale Oil	A-0 B-0	0.7	0.6	A-0 B-0	0.8	0.2
AL-8437-T	DFM from Paraho-II Shale Oil	A-0 B-0	0.9	1.0	A-0.5 B-1.2	1.4	1.0
AL-6400-T	Petroleum-Based JP-5	0.5	0.7	0.02	2.6	1.7	0.9

\* A and B are values obtained for duplicate bottles. The insoluble gum and precipitate values for bottles A and B are combined into one.

TABLE 10-4. DISSOLVED OXYGEN AND PEROXIDE LEVELS  
FOLLOWING STORAGE AT 43 C (10-1)

Code No.	Description	Initial		4 Weeks		8 Weeks	
		Dissolved O <sub>2</sub> , ppm	Peroxide Number*	Dissolved O <sub>2</sub> , ppm	Peroxide Number*	Dissolved O <sub>2</sub> , ppm	Peroxide Number*
AL-8466-T	JP-8 from Paraho-II Shale Oil	59	0	67	0	67	0.14
AL-8436-T	JP-5 from Paraho-II Shale Oil	72	0	69	0	60	0.06
AL-8437-T	DFM from Paraho-II Shale Oil	54	0	52	0	52	0.33

Code No.	Description	16 Weeks		32 Weeks	
		Dissolved O <sub>2</sub> , ppm	Peroxide Number*	Dissolved O <sub>2</sub> , ppm	Peroxide Number*
AL-8466-T	JP-8 from Paraho-II Shale Oil	**	**	45	0.24
AL-8436-T	JP-5 from Paraho-II Shale Oil	85	0.12	42	0.16
AL-8437-T	DFM from Paraho-II Shale Oil	46	0.35	34	0.39

\* Peroxide number is defined as the gram-equivalent of active oxygen in 1000 liters of fuel.

\*\* Sample lost.

TABLE 10-5. HYDROCARBON TYPE ANALYSES OF SHALE DERIVATIVES<sup>(10-1)</sup>

	<u>JP-8</u>	<u>JP-5</u>	<u>DFM</u>
FIA (as received)			
Aromatic, vol%	21	22	30
Olefin, vol%	2	2	1
Proton NMR (as received)			
Aromatic, vol%	16	14	15
Olefin, vol%	5	0	4
Proton NMR (32 weeks)			
Aromatic, vol%	15	13	16
Olefin, vol%	5	2	4
<sup>13</sup> C NMR (as received)			
Aromatic, wt%	15.4	14.3	15.0
<sup>13</sup> C NMR (32 weeks)			
Aromatic, wt%	15.0	15.6	13.2
Ultraviolet (as received)			
Aromatic Carbon			
Mono, wt%	13.84	13.54	11.58
Di, wt%	1.19	1.36	4.03
Tri, wt%	0.002	0.002	0.045

TABLE 10-6. COMPATIBILITY OF SHALE AND PETROLEUM JP-5 FUELS<sup>(10-1)</sup>

Code No. Fuel Description Test hr	AL-8436-T		AL-8570-T		AL-8436-T & AL-8570-T	
	Paraho-II	JP-5	Petroleum	JP-5	Blend 50/50	
	1.5	3.0	1.5	3.0	1.5	3.0
Color after test, D 1500 (1)	0.5	0.5	0.5	0.5	0.5	0.5
Glass Fiber Filter Rating, Visual (2)	1	5	15	19	12	15
% Reflectance (3)	93.9	86.0	50.8	32.0	68.8	55.0
Wt of particulates, mg/100 ml	0.08	0.12	0.56	1.04	0.26	0.48
Light Absorbance, 650 nm	0	0	0	0	0	0
575 nm	0	0.002	0	0.004	0	0
540 nm	0.001	0.007	0.006	0.015	0.001	0.005
500 nm	0.002	0.019	0.015	0.035	0.005	0.012
Adherent Insolubles, mg/100 ml	0.2	0.2	0.1	0.2	0.2	0.3
Steam Jet Gum on filtered sample, mg/100 ml	0.4	1.6	1.6	3.2	3.6	4.8

(1) Color of original samples and blends: 0.5

(2) Visual rating for all control filters: 1

(3) % Reflectance for all control filters: 99.0%

TABLE 10-7. COMPATIBILITY OF SHALE AND PETROLEUM DIESEL FUELS<sup>(10-1)</sup>

Code No. Fuel Description Test hr	AL-8437-F		AL-8277-F		AL-8437-F & AL-8277-F	
	Paraho-II	DFM	Petroleum	DF-2	Blend 50/50	
	1.5	3.0	1.5	3.0	1.5	3.0
Color D 1500 before test	0.5	0.5	1.5	1.5	1.0	1.5
after test	0.5	0.5	1.5	1.5	1.0	1.5
Glass Fiber Filter Rating, Visual (1)	1	2	17	20	8	20
% Reflectance Filter	95.8	94.1	40.5	18.5	79.0	27.5
Control	99.0	97.8	95.0	96.0	95.0	95.1
Wt of particulates, mg/100 ml	0.06	0.16	0.59	0.90	0.24	0.59
Light Absorbance, 650 nm	0	0.001	0.004	0.008	0	0.004
575 nm	0	0.008	0.023	0.031	0.011	0.019
540 nm	0	0.016	0.043	0.057	0.019	0.034
500 nm	0	0.035	0.088	0.114	0.040	0.067
Adherent Insolubles, mg/100 ml	0.2	0.2	0.2	0.2	0.1	0.2
Steam Jet Gum on filtered sample, mg/100 ml	1.2	3.8	4.0	4.2	16.0	13.6

(1) Visual rating for all control filters: 1

TABLE 10-8. CORROSION TENDENCIES OF SHALE-DERIVED FUELS<sup>(10-1)</sup>

	NACE Corrosion Ratings	
	Neat	25 PTB** FOA 15***
JP-8, AL-9089-SP	C	C
JP-5, AL-8436-T	C	B+
DFM, AL-8437-F	B	B++

\* NACE - National Association of Corrosion Engineers.

\*\* PTB - pounds per thousand barrels.

\*\*\* FOA 15 - Fuel oil additive 15 - candidate stabilizer additive for diesel fuel, Purchase Description PD ME-103.

Rating Descriptions:

A - no rusting	B - 5 to 25% rusting
B++ - less than 0.1% - 2 spots of no more than 1 mm in diameter	C - 25 to 50% rusting
B+ - less than 5% rusting	D - 50 to 75% rusting
	E - 75 to 100% rusting

B+, B++, and A are acceptable ratings for pipeline operation.

TABLE 10-9. GROWTH RATINGS OF CLADOSPORIUM RESINAE  
AT VARIOUS INCUBATION STAGES<sup>(10-1)</sup>

Fuel	Length of Time				
	30 days	60 days	90 days	120 days	6 Months
Shale JP-5	++	•	•	•	•
Shale DFM	+	•	•	•	•

\* Rating

+ = good growth  
• = heavy growth



AD-A145 159

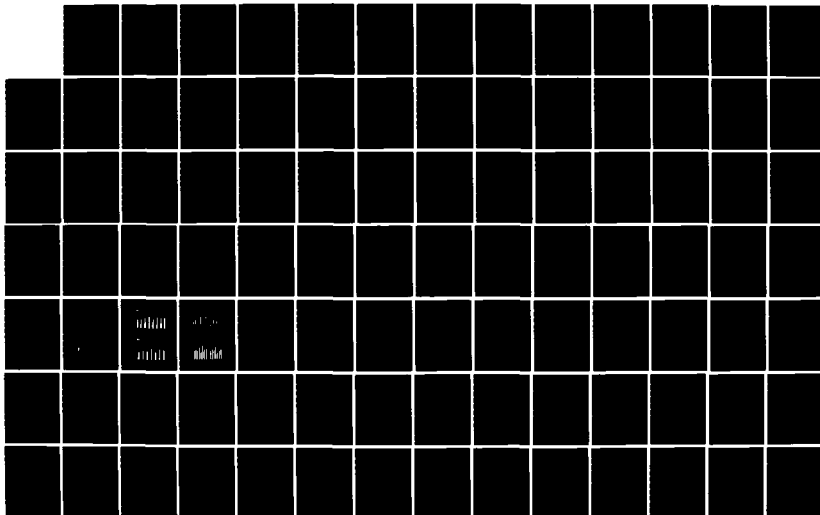
JOINT DOD/DOE SHALE OIL PROJECT VOLUME 3 TESTING OF  
REFINED SHALE OIL FUELS(U) BATTELLE COLUMBUS LABS OH  
H R HAZARD ET AL. DEC 83 N00014-83-C-0156

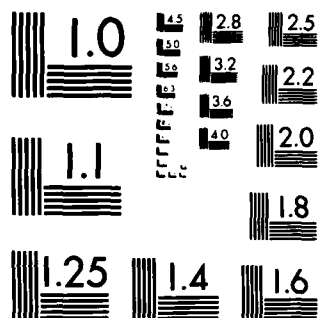
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MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

TABLE 10-10. SPECIFICATIONS OF DIESEL ENGINES TESTED BY AFLRL (10-1),  
UNIVERSITY OF WISCONSIN (10-3) AND CUMMINS ENGINE (10-4)

Manufacturer	Detroit Diesel	Teledyne Continental	Teledyne Continental*	J.I. Case	Cummins Engine
Designation	6V-53T	LDT-465-1C	CUE-1790	---	NTC-400
Induction System	turbocharged	turbocharged	simulated turbocharge	turbocharged	turbocharged
Combustion System	direct injection	M.A.N.	direct injection	direct injection	direct injection
Strokes/Cycle	2	4	4	4	4
Number of Cylinders	6	6	1	4	1
Arrangement	60° V	in-line	---	in-line	---
Displacement	5.21L <sup>3</sup> (318 in. <sup>3</sup> )	7.83L <sup>3</sup> (478 in. <sup>3</sup> )	2.44L <sup>3</sup> (149.1 in. <sup>3</sup> )	5.51L <sup>3</sup> (336 in. <sup>3</sup> )	2.36L <sup>3</sup> (144 in. <sup>3</sup> )
Bore and Stroke	9.84 x 11.43 cm (3-7/8 x 4-1/2 in.)	18.0 x 19.2 (4.56 x 4.87 in.)	(5.75 x 5.75 in.)	11.8 x 12.7 (4.625 x 5 in.)	14.0 x 15.3 (5.5 x 6.0 in.)
Rated Power at Speed kW(Hp) at rpm	244(300) at 2800	104(140) at 2600	---	--- at 2200	50(67) at 2100
Max Torque at Speed Nm(lb-ft) at rpm	834(615) at 2200	556(410) at 1600	---	---	---
Compression Ratio	17	22	---	15.8	14.5
Fuel System	N70 unit injector	Bosch PS86A-90EH- 5337A3 with ABD-355-124-7 nozzles	---	Bosch Type PES	Cummins PT high pressure system

\*Single cylinder from Teledyne-Continental AVDS-1790-2D engine adapted to a CUE crankcase by others.

TABLE 10-11. PERCENT CHANGE IN OBSERVED POWER OUTPUT AND  
BRAKE-SPECIFIC FUEL CONSUMPTION DUE TO OPERATION  
ON SHALE-DERIVED FUELS (DATA FROM REF. 10-1)\*

Engine	Power Output		Fuel Consumption	
	DFM	JP-5	DFM	JP-5
DDA 6V-53T	-1.7	-6.0	1.2	5.2
Teledyne-Continental AVDS-1790-2D	2.4	-2.7	-2.1	3.2
Teledyne-Continental LDT-465-1C	-0.7	----	1.3	----

\* Entries calculated as (shale fuel value) - (DF-2 value) \* 100% / (DF-2 value)

TABLE 10-12. SHALE DFM AND PETROLEUM DF-2 PHYSICAL PROPERTIES  
RELEVANT TO INJECTOR PERFORMANCE (10-2)

<u>Property</u>	<u>ASTM Procedure</u>	<u>Shale DFM</u>	<u>Petroleum DF-2</u>
Specific Gravity @ 40 C	D-1298	0.818	0.849
Kinematic Viscosity @ 40 C, cm <sup>2</sup> /S	D-445	2.68	2.70
Flash Point, C	D-93	75	58
Calorific Value, Kcal/Kg	D-2382-76	10,970	10,700
Reid Vapor Pressure, psi	D-323	0.55	0.30
Cloud Point, C	D-2500	-20	-17
Pour Point, C	D-97	-19	-21
Bulk Modulus, psi	----	140,000	193,000

TABLE 10-13. AVERAGE CHANGE IN NO<sub>x</sub> EMISSIONS FOR THREE TEST FUELS RELATIVE TO PETROLEUM FUEL EMISSIONS (DATA FROM REFERENCE 10-3)

<u>Fuel</u>	<u>Petroleum DF-2</u>	<u>Shale DFM</u>	<u>SRC-II Blended With T-17</u>	<u>DF-2 Doped With Pyridine</u>
Nitrogen Content (% by Mass)	0.02	0.024	0.344	1.0
Aromatic Content (% by Volume)	23	22	32	28
NO <sub>x</sub> Emissions Relative to Referee Fuel*	----	-8.7	3.6	-0.03

\* Calculated as (Test Fuel NO<sub>x</sub>) - (DF-2 NO<sub>x</sub>) \*100% / (DF-2 NO<sub>x</sub>)

TABLE 10-14. RESULTS OF ALLISON T-63 COMBUSTOR  
TESTS PERFORMED BY AFLRL<sup>(10-1)</sup>

Power Point	Fuel No.	Fuel Type	Flame Radia.	Smoke No.	Smoke mg/M <sup>3</sup>	NO <sub>x</sub> E.I.	CO E.I.	UBH E.I.	Combustion Efficiency
100	0	Jet A	42.8	28.9	4.3	7.2	9.5	0.2	99.79
100	1	JP-5	59.7	48.7	13.2	7.2	9.1	0.4	99.78
100	2	DFM	60.1	45.2	10.8	6.7	13.8	0.4	99.67
75	0	Jet A	37.0	32.1	5.1	5.5	30.3	2.0	99.31
75	1	JP-5	48.9	38.1	7.1	5.7	30.8	1.9	99.28
75	2	DFM	50.7	41.0	8.46	4.7	34.3	2.9	99.13
55	0	Jet A	31.9	15.8	1.8	4.7	48.3	7.1	98.64
55	1	JP-5	43.7	19.7	2.4	4.6	47.7	7.3	98.59
55	2	DFM	48.1	22.6	2.9	4.3	50.1	7.0	98.54
40	0	Jet A	26.7	12.0	1.3	4.7	59.6	11.7	98.14
40	1	JP-5	37.4	25.2	3.4	4.7	59.9	13.3	97.97
40	2	DFM	43.2	27.9	4.0	4.7	65.4	12.5	97.91
25	0	Jet A	23.3	11.7	1.27	3.1	82.3	35.9	95.57
25	1	JP-5	30.0	21.2	2.6	3.6	75.8	30.7	96.13
25	2	DFM	39.2	29.9	4.5	3.3	102.3	33.7	95.35
10	0	Jet A	17.8	7.9	0.84	1.3	113.6	71.5	92.37
10	1	JP-5	26.2	17.7	2.06	3.3	107.9	82.9	91.52
10	2	DFM	31.9	23.2	3.0	3.1	118.0	69.0	92.42

TABLE 10-15. IDLE PERFORMANCE DATA FOR THE  
AGT 1500 RECORDED BY AVCO-LYCOMING<sup>(10-6)</sup>

FUEL	AMBIENT TEMPERATURE SIMULATION	GAS ANALYSIS FUEL/AIR RATIO	INEFFICIENCY UNC	NO <sub>x</sub> as NO <sub>2</sub> CO E1	EFFICIENCY	SMOKE NO.	TVR*
DF-2	0°	.00616	1.125	1.374 3.469	97.50	3.1	--
	60°	.00658	.221	.681 4.76	99.09		
	60°	.00661	.226	.715 4.78	99.02	6.5	1.368
SHALE	0°	.00665	.427	.870 3.75	98.70		
	0°	.00661	.456	.852 3.98	98.69	2.3	1.295
DFM	60°	.00709	.328	.775 4.14	98.90		
	60°	.00696	.317	.796 4.17	98.89	3.4	1.232
SHALE	0°	.00549	1.062	1.166 2.96	97.77		
	0°	.00608	.611	.941 3.32	98.44	1.0	1.344
JP-5	60°	.00722	.154	.596 4.70	99.25		
	60°	.00688	.215	.664 4.62	99.12	3.4	1.262

\* TVR = Temperature Variance Ratio  
=  $(T_{max} - T_{in}) / (T_{over} - T_{in})$

TABLE 10-16. CHARACTERISTICS OF ENGINES SUBJECTED TO SHALE DFM  
ENDURANCE TESTS(10-1,8,9)

<u>Engine</u>	<u>Cummins NTC-400</u>	<u>Caterpillar 3208NA</u>	<u>Detroit Diesel 3-53</u>
Cylinder Configuration	in-line 6	V-8	in-line 3
Bore, in.	5.5	4.5	3.875
Stroke, in.	6.0	5.0	4.5
Displacement, in. <sup>3</sup>	855	636	159
Rated HP @ RPM	400 @ 2100	210 @ 2800	90 @ 2800
Aspiration	Turbocharged	Natural	Natural
Cycle	4-Stroke	4-Stroke	2-Stroke
Injection	Direct	Direct	Direct



TABLE 10-17. NATO STANDARD CYCLE EMPLOYED IN ENGINE  
ENDURANCE TESTS AT TACOM(10-9)

<u>Period</u>	<u>Percent Rated Speed</u>	<u>Percent Load</u>	<u>Time Hours</u>
1	Idle	0	1/2
2	Max Torque	100	1/2
3	100	0	1/2
4	75	85	1
5	100	50	1/2
6	100	100	1
7	50	25	1/2
Total Duration:			5

TABLE 10-18. CUMMINS NTC-400 PERFORMANCE BEFORE AND AFTER NATO  
CYCLE 400-HOUR ENDURANCE TEST ON SHALE DFM(10-8)

		Petroleum DF2	Shale DFM	Shale JP-5
Maximum Power (Brake HP @ RPM)	Before	407	414	401
		2100	2100	2100
	After	407	409	390
		2100	2100	2100
Maximum Torque (Ft-Lb @ RPM)	Before	1204	1213	1200
		1500	1300	1300
	After	1209	1207	1190
		1300	1300	1300
Minimum Fuel Consumption (LB/HP-Hr @ RPM)	Before	0.359	0.353	0.347
		1700	1700	1700
	After	0.347	0.350	0.344
		1700	1700	1700

TABLE 10-19. CATERPILLAR 3208NA PERFORMANCE BEFORE AND AFTER  
NATO CYCLE 400-HOUR ENDURANCE TEST ON SHALE  
DFM(10-9)

		Petroleum DF-2	Shale DFM	Shale JP-5
Maximum Paper (Brake HP @ RPM)	Before	204	202	185
		2800	2800	2600
	After	204	202	204
		2800	2800	2800
Maximum Torque (Ft-LB @ RPM)	Before	498	488	480
		1400	1200	1400
	After	500	505	365
		1200	1400	1200
Minimum Fuel Consumption (LB/HP-HR @ RPM)	Before	0.367	0.368	0.351
		2000	2000	2000
	After	0.362	0.370	0.358
		2000	1400	2000

TABLE 10-20. SMOKE METER READINGS DURING TESTING OF THE CUMMINS NTC-400(10-8)

Engine	RPM	Before Endurance		100 Hrs Shale DFM	200 Hrs Shale DFM	300 Hrs Shale DFM	After Endurance	
		Shale DFM	Shale JP-5				Shale DFM	Shale JP-5
							DF-2	
1300		1.1	0.9	0.9	1.2	0.6	1.2	0.8
1500		0.5	0.7	0.5	0.7	0.4	0.6	0.6
1700		0.6	0.5	0.4	0.7	0.4	0.5	0.4
1900		0.5	0.8	0.4	0.6	0.3	0.5	0.5
2000		0.6	0.9	0.3	0.6	0.4	0.6	0.5
2100		0.6	1.0	0.6	0.7	0.5	0.6	0.7

10-35

Classification

Visual Description of Smoke

Clear	1-2
Light Grey	2-3
Medium Grey	3-4
Dark Grey	4-6
Black	6-10

TABLE 10-21. SMOKE METER READINGS DURING TESTING OF THE CATERPILLAR 3208NA(10-9)

Engine RPM	BEFORE ENDURANCE						100 HOURS						200 HOURS						300 HOURS						AFTER ENDURANCE					
	DF-2			JP-5			DFM			DFM			DFM			DFM			DFM			DF-2			JP-5			DFM		
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R		
2800	2.2	2.0	1.6	2.4	2.2	3.4	3.8	2.5	2.9	2.6	2.0	1.7	3.2	3.4	4.1	3.3	1.9	2.2												
2600	2.4	2.0	1.4	2.0	2.2	2.2	3.2	2.4	3.2	2.4	1.8	2.0	2.8	3.0	2.4	2.0	2.4	2.0												
2400	2.1	3.2	1.5	1.8	2.1	2.3	3.4	1.8	3.8	1.9	1.6	1.7	2.8	3.1	2.3	3.1	2.2	1.8												
2200	2.4	2.2	1.7	1.6	2.2	2.3	3.5	1.8	3.4	2.5	1.3	2.4	2.6	3.2	2.0	3.2	1.9	1.8												
2000	2.0	2.2	1.8	2.1	2.4	2.2	2.0	1.8	2.8	1.8	1.0	1.2	2.6	0.7	1.4	1.4	1.4	1.5												
1800	2.4	2.2	1.8	1.9	2.3	3.2	2.6	2.2	2.6	2.3	1.4	1.4	2.4	2.8	1.4	1.6	1.4	1.6												
1600	1.7	2.0	1.6	2.1	2.4	2.9	2.2	1.5	2.5	1.9	1.1	3.0	2.4	2.0	1.4	1.3	2.2	2.0												
1400	2.4	2.5	1.7	3.0	2.6	2.9	3.8	2.4	3.4	3.1	1.6	2.4	2.6	2.4	1.8	1.4	2.2	1.9												
1200	4.2	3.2	2.8	4.0	3.4	3.0	4.6	3.3	2.5	3.6	1.6	1.6	2.7	2.8	1.6	2.0	2.0	2.3												

Visual Description of Smoke	Classification
-----------------------------	----------------

Clear	1-2
Light Grey	2-3
Medium Grey	3-4
Dark Grey	4-6
Black	6-10

TABLE 10-22. SHALE FUEL PROPERTIES OF CONCERN FOR GASOLINE ENGINES<sup>(10-10)</sup>

<u>Fuel Property</u>	<u>Area of Concern</u>	<u>Potential Resolution</u>
Octane Number	Decrease causes poor performance, poor life	Control by specification, test by 640.1C (maximum power) and 690.1C (endurance)*
Reid Vapor Pressure	High RVP causes vapor lock while low RVP causes difficult cold starting	Control by specification, test by 710.1C (high temperature) and 701.1C (extreme cold starting and operating)
Water & Sediment	High water and sediment causes filter pluggage and poor performance	Control by specification
Sulfur content	High sulfur content causes decreased engine life, high emissions and elastomer degradation	Control by specification
Aromatic content	High aromatic content causes elastomer degradation and decreased engine life	Monitor & record, test by 690.1C (endurance)
Oxidation stability	Low oxidation stability causes poor performance and difficult starting	Control by specification

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\*Test numbers refer to procedures from MIL-STD-705B Generator Sets, Engine Driven, Methods of Tests and Instructions(33)

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TABLE 10-23. SHALE FUEL PROPERTIES OF CONCERN FOR DIESEL ENGINES<sup>(10-10)</sup>

<u>Fuel Property</u>	<u>Area of Concern</u>	<u>Potential Resolution</u>
Lubricity	Low lubricity causes pump wear, poor performance, decreased engine life.	Test by fuel system bench and/or 690.lC (endurance)*
Naphthene content	Effect of naphthenes on elastomers largely unknown, possible elastomer degradation and decreased engine life.	Test by fuel system bench tests and/or 690.lC (endurance).
Cetane Number	Low cetane number causes poor performance, poor startability, decreased engine life.	Control by specification, test by 701.lC (extreme cold starting) and 640.lC (maximum power)
Cloud point	High cloud point causes poor cold weather performance and startability.	Control by specification, test by 701.lC (extreme cold start)
Volatility	Low volatility causes poor atomization and poor performance, high volatility causes vapor lock, poor starting, pump wear and decreased engine life.	Control by specification, test by fuel system bench tests, 710.lC (high temperature), 701.lC (extreme cold), 720.lC (altitude), 690.lC (endurance)
Viscosity	High viscosity causes poor atomization and poor performance, low viscosity causes pump wear and decreased engine life.	Control by specification, test by fuel system bench tests, 710.lC (high temperature), 701.lC (extreme cold), 720.lC (altitude), 690.lC (endurance)
Sulfur content	High sulfur content causes engine corrosion, deposits, decreased engine life.	Control by specification
Water and sediment	High water and sediment cause filter pluggage, poor performance, decreased engine life.	Control by specification
Carbon residue	High carbon residue contributes to deposits, poor performance, decreased engine life.	Control by specification, test by 690.lC (endurance).
Stability	Low stability causes filter pluggage, poor performance, decreased engine life, poor startability.	Control by specification

\*Test numbers refer to procedures from MIL-STD-705B, Generator Sets, Engine Driven, Methods of Tests and Instructions.

TABLE 10-24. SHALE FUEL PROPERTIES OF CONCERN FOR GAS TURBINE ENGINES<sup>(10-10)</sup>

<u>Fuel Property</u>	<u>Area of Concern</u>	<u>Potential Resolution</u>
Lubricity	Low lubricity causes pump wear, poor performance, decreased engine life.	Test by fuel system bench tests and/or 690.lC (endurance)*
Naphthene content	High naphthene content may cause elastomer degradation, decreased engine life.	Test by fuel system bench tests and/or 690.lC (endurance).
Freezing point	High freezing point causes filter plugging and poor starting at cold temperatures	Control by specification, test by 701.lC (extreme cold start)
Volatility	Low volatility causes difficult starting in cold temperatures.	Control by specification, by fuel system bench tests, 710.lC (high temperature), 701.lC (extreme cold), 720.lC (altitude)
Viscosity	High viscosity causes low temperature pumpability problems, low viscosity causes pump wear and decreased engine life	Control by specification, test by fuel system bench tests, 701.lC (extreme cold start), 690.lC (endurance).
Sulfur content	High sulfur content causes engine corrosion, high emissions, decreased engine life.	Control by specification, test by fuel system bench test and/or 690.lC (endurance)
Hydrogen content	Low hydrogen content may cause increased combustor liner temperature, decreased engine life	Control by specification, test by 690.lC (endurance)
Aromatic content	High aromatic content causes increased combustor liner temperature, decreased engine life.	Control by specification, test by 690.lC (endurance)
Contaminants	High contaminants cause filter pluggage, pump wear, decreased engine life, hard starting	Control by specification
Stability	Low stability causes filter pluggage, difficult starting, decreased engine performance	Control by specification

\*Test numbers refer to procedures from MIL-STD-705B, Generator Sets, Engine Driven, Methods of Tests and Instructions.



## 11. DOE ALTERNATE FUELS PROGRAM ENGINE TESTS

### Introduction

The Department of Energy (DOE) has an ongoing program to develop technology for use of alternate fuels for highway, railway, and marine transportation. As part of this program DOE has sponsored tests of various engines with shale DFM and shale JP-5 fuels. These have included tests of high-speed, medium-speed and low-speed diesel engines, gasoline engines, and a Stirling engine, and studies of future cost, availability, and characteristics of alternative future fuels. The fuels evaluated have included shale fuels, coal-derived liquids, ethanol, methanol, petroleum fuels having broadened specifications, and blends of petroleum and non-conventional fuels. Only the shale fuel tests will be discussed here.

Table 11-1 lists the DOE projects in which shale DFM or shale JP-5 have been evaluated. Projects in which shale residual fuel were evaluated are included in Section 14. The joint DOE/TACOM project with Cummins Engine Company, on the adiabatic diesel engine, is reported in Section 10.

### Refining Studies and Engine Testing of Alternative Highway Transportation Fuels (Reference 11-1)

This project was carried out by Southwest Research Institute under contract with the Department of Energy.

### Objectives

The overall objective of this multifaceted study was to assess refining capabilities and automotive engine compatibility for several alternative fuels. Objectives of the three major phases of the project were to (1) use linear programming models to show how shale oil and coal liquids will be refined and used as domestic transportation fuels; (2) formulate and blend fuels suitable for automotive engines from alternative feed-stocks; and (3) subject the alternative fuels to a broad range of tests in spark and compression-ignition engines. Because only the third phase of the project dealt directly with the use of the subject shale fuels in internal combustion engines, the first two phases are not covered in this review.

### Procedure

An extensive property evaluation was performed on shale DFM, shale JP-5, DF-2 and several other alternative fuels. Blends of shale and petroleum fuels were also prepared and evaluated. The shale fuels, blends, and DF-2 were burned in a single-cylinder Cooperative Lubricant Research (CLR) engine at 75 percent of full load and at 3 speeds. Fuel consumption, particulates, NO<sub>x</sub>, and hydrocarbons (HC) were recorded for each alternative fuel and compared to values for DF-2.

A lubricity test was performed on the shale DFM using a ball-on-cylinder machine with a 1000-g load on the ball.

### Results

Table 11-2 presents analyses of the shale DFM, shale JP-5, and two blends containing shale DFM and shale JP-5. The two blends have wider distillation ranges and higher aromatic contents than the shale DFM and shale JP-5. The blend identified as case 2A is more than 50 percent by volume shale-derived fuel, while the case 3 blend is roughly 34 percent shale-derived.

Figure 11-1 summarize the fuel consumption and emissions results for the four alternative fuels relative to the DF-2 results. Data are reported at three rotational speeds (1000, 1500, and 2000 RPM) for each fuel. In terms of fuel consumption, 3 of the 9 alternative fuels exhibited performance essentially identical to that of DF-2. The shale JP-5 fuel consumption was roughly 10 percent less than that for the DF-2. Particulate and NO<sub>x</sub> emissions shown in Figure 11-1 are essentially trendless and equivalent to the DF-2 results with the exception of significantly lower JP-5 particulate emissions. Hydrocarbon emissions summarized in Figure 11-1 are lower than the DF-2 values for 3 of the 4 alternatives fuels; shale JP-5 is once again the exception, exhibiting the relatively high HC emissions typical of a lower boiling range product.

The lubricity test performed on shale DFM yielded an average wear scar diameter of 0.55 mm, characteristic of a fuel with poor lubricity. In contrast, the DF-2 had good lubricity, as indicated by a wear scar diameter of 0.38 mm.

### Conclusions

Shale DFM, shale JP-5 and two blends of shale and petroleum-derived fuels were evaluated as part of an extensive alternative fuels study. Fuel economy and emissions results for the four fuels were largely similar to those achieved with DF-2. A lubricity test revealed that the shale DFM under investigation had poor lubricity, possibly a consequence of substantial hydrotreating. The results suggest that

any of the subject alternative fuels should perform acceptably as substitutes for conventional petroleum-derived diesel fuel.

Tests of EMD 567B Medium-Speed Diesel Engine  
With Shale Fuels  
(Reference 11-2)

Introduction

Tests of a two-cylinder EMD 567B medium speed diesel with shale DFM were carried out by Southwest Research Institute as part of a multi-year project to investigate the use of alternative fuels in medium-speed diesel engines. The project is supported jointly by DOE, the Federal Railroad Administration, the General Electric Co., the Electro-Motive Division of General Motors, the Association of American Railroads, and by individual railroads. Three test engines are being used: the 2-cylinder EMD 567B laboratory engine, an EMD 645 E3b 12-cylinder turbocharged locomotive engine, and a GE 7FDL 12-cylinder turbocharged locomotive engine. The shale DFM was evaluated only in the 2-cylinder engine.

Procedure

The shale DFM and a DF-2 were used in performance and emission tests of the EMD 567B engine. Test data were taken at the even-numbered notch positions (standard throttle positions in locomotives), from idle to full power. Data included horsepower output, thermal efficiency, rate of pressure rise, ignition delay, and peak cylinder pressure. Emission data included NO<sub>x</sub>, CO, HC, SO<sub>2</sub> and particulates. Fuel rates were set on an equal-volume basis, injecting the same amount of shale DFM or DF-2 at each notch position.

Results

Table 11-3 lists fuel analyses for the shale DFM and the DF-2 used as a baseline fuel. The shale DFM was found to meet all specifications for DF-2.

Figures 11-2 through 11-4 present test results. Engine performance with shale DFM was comparable to that with DF-2 in every respect. Engine thermal efficiency, matched that with DF-2 throughout the notch schedule. Brake horsepower was typically 3 percent below that for the DF-2 at all notch positions, corresponding to a 3 percent lower heat input when injecting fuel on an equal-volume basis. The cylinder pressure data showed a slight reduction in ignition delay in Notches 2 and 3 with shale DFM. Rates of pressure rise and peak cylinder pressures were essentially equal to values for DF-2.

Figure 11-4 shows exhaust emission results for shale DFM and DF-2. No significant variations from DF-2 emissions were found.

### Conclusions

Properties of shale DFM were found to be within limits for DF-2. Engine operation with shale DFM was normal in every respect. It appears that shale DFM can be handled and used like DF-2 without problems.

### Performance and Emissions of the John Deere 6466-T Engine (Reference 11-3)

Performance and emission tests of the John Deere Model 6466-T diesel engine were carried out as an in-house project at the DOE Bartlesville Energy Technology Center, Bartlesville, Oklahoma. The objective of these tests was to compare the performance and emissions of this engine when burning shale DFM and shale JP-5 with those when burning DF-2.

### Procedure

Each of the three fuels was burned in short-term tests of the John Deere 6466-T 6-cylinder turbocharged engine of 466 cubic inch displacement. The engine was operated over the EPA 13-mode cycle with each fuel. Results were reported for operation at idle and rated speed; results for other loads were not determined because of fuel metering problems. Fuel consumption, and emissions of  $\text{NO}_x$  and hydrocarbons were measured.

### Results

Fuels were analyzed to determine specific gravity, aromatic content, and distillation range, with the results listed below:

	Petroleum DF-2	Shale JP-5	Shale DFM
Specific gravity,	0.852	0.808	0.835
Aromatics FIA, vol-pct...	28	21	31
Distillation, F:			
10 pct.....	430	380	450
50 pct.....	510	400	510
90 pct.....	570	450	560

The shale DFM and DF-2 were quite similar, although the shale DFM has a somewhat narrower boiling range, lower specific gravity, and higher aromatic content than the DF-2. The shale JP-5 is a lighter fuel than the diesel fuels.

Fuel consumption at the rated speed of 2200 RPM as a function of load was virtually identical for the three fuels. Likewise, no significant differences were observed in NO<sub>x</sub> production for the three fuels. Hydrocarbon (HC) emissions for the two diesel fuels were quite similar. However, HC emissions when burning shale JP-5 were as much as 23 percent higher than those observed with either of the diesel fuels. At full load, the shale JP-5 HC emissions were essentially identical to those produced by the diesel fuels.

### Conclusions

The fuel efficiency and NO<sub>x</sub> emission levels of a John Deere 6466-T diesel engine were insensitive to fuel type when burning DF-2, shale JP-5, and shale DFM. Hydrocarbon emissions at partial load were significantly higher with shale JP-5. Either of the two shale-derived fuels appears to be a satisfactory substitute for DF-2 on the basis of these results.

### Tests of Superior 40-X-6 Medium-Speed Diesel Engine (Reference 11-4)

Tests of the Superior 40-X-6 engine were carried out by the Superior Division of Cooper Energy Services under subcontract to Energy and Environmental Research Corporation, under a DOE-BETC project. Two fuels were evaluated relative to DF-2: shale DFM, and a blend of 30 percent shale DFM and 70 percent petroleum No. 5 residual fuel oil. The Superior 40-X-6 engine is a large stationary engine with a 9-1/8-in. bore and 1-1/2-in. stroke. It is a turbocharged, 4-stroke, 6-cylinder engine developing 710 HP at 900 RPM.

### Objectives

The primary objective of this project was to identify problems associated with running a large stationary diesel engine on alternate fuels. The areas investigated were fuel storage and handling, fuel injection, ignition and combustion, emissions, and wear.

### Fuel System Materials Immersion Tests

Fuel system materials in direct contact with fuel were immersed in DF-2, shale DFM and the 30-70 blend. After one year of immersion in the shale DFM, and three months of immersion in the 30-70 blends, there was no evidence of problems with elastomers or metals.

### 300-Hour Injector Rig Tests

A simulated fuel system that included a fuel reservoir, filters, a motor-driven fuel pump, and an injector was operated for 300 hours on each fuel. Before and after the 300-hour test the fuel spray was evaluated, and injector pressure and delivery rates measured. After 300 hours the injection system was dismantled and checked for wear and deposits. There was no detectable wear, erosion, or deposits associated with any of the fuels.

### Single-Cylinder Test

The 6-cylinder engine is set up to permit firing of a test fuel in one cylinder while operating the other five cylinders on DF-2. The test cylinder is instrumented to measure injector fuel pressure and cylinder pressure as a function of crank angle. This type of test has the advantages that tests are at full scale, the engine can be operated at any desired speed and load independently of combustion of the test fuel, and fuel system parameters for the test cylinder can be varied over a wide range without concern for keeping the engine running.

Results of single-cylinder tests with shale DFM, relative to results with DF-2, were as follows:

1. Fuel consumption with shale DFM was 5 to 10 percent higher, with the greatest increase at 900 rpm.
2. The maximum firing pressure was 3 to 5 percent lower with shale DFM, with the greatest difference at 900 rpm.
3. The ignition time lag with shale DFM was 15 to 22 percent shorter than with DF-2.
4. The rate of pressure rise with shale DFM was 1 to 5 percent greater than for DF-2, but knock did not occur.

Results of single-cylinder tests with the blend of 30 percent shale DFM and 70 percent No. 5 residual fuel, relative to results with DF-2, were as follows:

1. Fuel consumption increased 3 to 10 percent, with the greatest increase at 900 rpm.
2. The maximum firing pressure was the same as for DF-2.
3. The ignition time lag with the blended fuel was 10 to 22 percent shorter than for DF-2.
4. The rate of rise in firing pressure was 40 to 80 percent greater than for DF-2. Diesel knock occurred at 600 rpm and 50 percent load.

### Full Engine Test

The full engine test was run with the fuel system arranged to fire experimental fuel in all six cylinders. The objective was to verify results of single-cylinder tests and evaluate factors related to overall engine operation. The injection timing and nozzle tip which produced best results in the single-cylinder tests also proved best in the engine tests.

Figures 11-5 and 11-6 show the brake specific fuel consumption (BSFC) and the average maximum firing pressure for the three fuels plotted against brake horsepower for an engine speed of 900 RPM. It is seen that BSFC is similar for shale DFM and DF-2, but considerably higher for the 30-70 fuel blend. Maximum firing pressure is similar for DF-2 and shale DFM, but lower for the 30-70 fuel blend.

Figure 11-7 shows emissions of  $\text{NO}_x$  over a range of loads at 900 RPM. These curves show that  $\text{NO}_x$  emissions when firing shale DFM are slightly higher than when firing DF-2, and  $\text{NO}_x$  emissions when firing the 30-70 blend are considerably lower than when firing DF-2. The lower  $\text{NO}_x$  with the fuel blend is probably due to lower cylinder temperatures resulting from slower combustion of the residual fuel.

Figure 11-8 shows emissions of CO and HC over a range of loads at 900 RPM. HC values for shale DFM are slightly lower than those for DF-2, while HC values for the 30-70 fuel blend are slightly higher. CO emissions for both shale DFM and the 30-70 fuel blend are moderately lower than for DF-2 over most of the load range, although higher for the 30-70 fuel blend at the highest load point.

Particulates were measured at 900 RPM and 100 percent load by the Energy an Environmental Research Corporation using the Sass Train System. Particulate matter washed from the probe after each test was added to the size range greater than 10 microns.

Table 11-5 summarizes particulate mass loadings, elemental analyses, and particle size distributions for these tests. Particulate loading is slightly higher for shale DFM, and slightly lower for the 30-70 blend than for DF-2.

Table 11-6 summarizes the results of analyses of the particulates for polynuclear aromatic hydrocarbons (PAH). Inspection of these results shows that PAH distribution is similar for all three of the test fuels.

### Conclusions

It was concluded that the Superior 40-X-6 engine could be run on shale DFM without modification, with a penalty of 1 to 7 percent in fuel consumption. Emissions, deposits, and wear were all similar to those with DF-2, within the acceptable range.

Operation of the engine with the 30-70 blend would require additional supporting equipment. Filtration problems required addition of a 30-micron filter upstream of the standard 5-micron filter, and it was necessary to heat the fuel to avoid collection of wax in the filters. Carbon deposits were similar to DF-2. Emissions were moderate, although  $\text{NO}_x$  was somewhat higher than for DF-2. However, there was substantial ring wear with the fuel blend not experienced with the other fuels. It was concluded that this fuel blend performed surprisingly well, and that other blends should be investigated, perhaps in the 35-65 or 40-60 range, to reduce ring wear.

Test of Wichmann 1AX Medium-Speed Diesel Engine  
(References 11-5, 6)

Introduction

A project on the use of alternative fuels in medium-speed and slow-speed diesel engines is being carried out at the Marine Technology Center at Trondheim, Norway, a facility shared by the Norwegian Institute of Technology and the Ship Research Institute of Norway. A number of petroleum residual fuels, blends of SRC II distillates with marine diesel fuel, and shale DFM have been evaluated during this project. (11-5,6)

Objective

The objective of these tests was to compare the combustion characteristics, efficiency, and emissions of the Wichmann 1AX medium speed single-cylinder diesel engine when burning shale DFM with those when burning marine diesel oil (MDO). Analyses of these fuels are summarized in Table 11-7.

Procedure

A heavily instrumented Wichmann 1AX single-cylinder, two stroke, medium-speed diesel engine was used to compare two fuels. It has a bore of 300 mm (11.8 in.) stroke of 450 mm (17.7 in.), and speed of 375 RPM. Performance and emissions were measured in short-term tests at a constant speed of 375 RPM, at loads from idle to 106.5 percent of rated capacity of 110 Kw. Fuel consumption and emissions of  $\text{CO}$ ,  $\text{HC}$ ,  $\text{NO}_x$  and particulates were measured. In addition, cylinder pressure, injection pressure, cylinder-head surface temperature, and flame radiation were monitored for both fuels. Dynamic surface temperatures were measured with thermocouples and flame radiation was measured through a quartz window with a photodiode.



## Results

Cylinder pressure, temperature, and radiation measurements revealed no qualitative differences in the combustion characteristics of the MDO and the shale DFM. These apparent similarities carried over to the fuel consumption and most of the emissions measurements as well. An unweighted average of brake specific energy consumptions at five engine loads indicates that the engine was 1.2 percent less efficient while burning shale DFM than when burning MDO. This small difference was attributed by the author to the fact that the injector was optimized for the MDO rather than the less viscous shale DFM.

NO<sub>x</sub> and HC emissions were virtually identical for the two fuels regardless of load. CO emissions were slightly higher when burning shale DFM, particularly at higher loads. Particulate emissions at all loads except idle were substantially higher when burning shale DFM. Here again, the higher emissions levels with shale DFM may be the result of a non-optimum injector configuration.

## Conclusions

MDO (marine diesel oil) and shale DFM were burned in a Wichmann 1AX single-cylinder diesel engine at 375 RPM over a wide load range. Fuel consumption was nearly identical for the two fuels. NO<sub>x</sub> and HC emissions were also quite similar. Higher CO and particulate emissions observed when burning shale DFM may have been due to burning the shale fuel with an injector optimized for the more viscous MDO. Cylinder pressure, temperature, and radiation traces revealed no qualitative differences in engine operation when burning the two fuels.

### General Electric Co. Tests of Type FDL Locomotive Diesel Engines (Reference 11-7)

General Electric, under contract to DOE, has carried out extensive tests of railroad locomotive type diesel engines to evaluate the use of shale DFM, SRC-II (a coal-derived liquid fuel) residual oil, and blends of these with DF-2 as potential fuels or fuel extenders for use in locomotives. The General Electric Type FDL diesel engines tested were medium speed, high-output, heavy duty, four-stroke-cycle, turbocharged and intercooled engines having a bore of 9 in., stroke of 10.5 in., and normal operating speed of 450 to 1050 rpm. More than 20,000 engines of this class are used by U.S. railroads, and others are used for marine service. Reference 11-7, which summarizes this work, contains much information on results of tests with blends of DF-2 with SRC-II and with residual oil. However, only the results of tests with shale DFM and its blends will be summarized herein.

### Objective

The objective of this project was to assess the possibility of introducing shale DFM, SRC-2, or residual oil as fuels or blending components for locomotive fuels. The work with shale DFM include tests with neat shale DFM, and with DF-2 blends containing 20 to 80 percent shale DFM.

### Procedure

Shale DFM, and blends of shale DFM with DF-2 were analyzed. Compatibility of the fuels with fuel-system materials was evaluated in immersion tests and in bench-scale tests of fuel pumps and injectors. A two-cylinder engine having cylinders, pistons, and cylinder heads interchangeable with those of commercial engines was used to determine peak cylinder pressures, specific fuel consumption, exhaust emissions, and particulate emissions for the test fuels. An 8-cylinder engine was then used for 100-hour durability tests in which piston ring wear, cylinder liner wear, deposits and deterioration of lubricating oil were evaluated.

Figure 11-9 shows a cross-section of the eight-cylinder Type FDL engine used for these tests.

### Results of Two-Cylinder Engine Tests

Table 11-8 summarizes analyses of DF-2, shale DFM, and blends used for tests of the two-cylinder engine. The properties of the shale DFM are very similar to the properties of the DF-2.

Table 11-9 summarizes exhaust emissions for DF-2, shale DFM, and their blends at three power levels. The differences in emissions are small and appear insignificant.

Particulate emissions and Bosch Smoke No. varied considerably for two samples of DF-2. The values for a blend of 50 percent shale DFM with DF-2 were close to the lower values for DF-2 and do not appear to be significantly different from values for DF-2.

Figure 11-10 shows that specific fuel consumption for shale DFM, and for blends with DF-2, was slightly higher than the average value for DF-2, but well within the range of values for DF-2 alone.

Table 11-10 shows piston temperatures measured on both the intake-valve side and the exhaust-valve side, at three vertical locations. Temperatures for all locations were nearly identical for shale DFM, DF-2, and blends of the two fuels.

Table 11-11 shows peak cylinder pressures measured at three loads. Values for shale DFM were slightly higher than those for DF-2 at ratings of 100 hp/cylinder and 20 hp/cylinder, and were somewhat lower at 206 hp/cylinder. The differences do not appear significant.

#### Results of Durability Tests of Eight-Cylinder Engine

Two 100-hour durability tests were run with DF-2 fuel, and one 96-hour test was run with a blend of DF-2 with 50 percent shale DFM. The piston-ring end gap, the weight loss of the top compression ring, and the increase in cylinder diameter were measured after each test. These measurements showed that wear was very small, and similar in value for all of the fuels tested. The normal life of piston rings is 15,000 to 25,000 hours, so that normal wear in a 100-hour period is very small.

Figure 11-11 shows the ratio of specific fuel consumption for several fuel blends tested to that for DF-2, before and after each 100-hour test. The differences between values at the beginning and end of each test are small. However, the specific fuel consumption for the shale DFM blend was about 1 percent higher than for DF-2.

Table 11-12 shows changes in lubricating oil properties during 100-hour test periods for several fuel blends. The increase in viscosity and the increase in pentane insolubles was greater for the shale DFM blend than for DF-2, and the reduction in alkalinity was also greater for the shale DFM blend.

#### Conclusions from General Electric Tests

It was concluded that shale DFM, either alone or in blends with DF-2, can be used without significant consequences in a medium-speed, high-horsepower, 4-cycle diesel engine.

#### References

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- 11.7 Hoffman, J. G. and Martin, F., "Coal-Liquid Fuel/Diesel Engine Operating Compatibility", Final Report, DOE/BC/10110-T1 (DE84006062), Sept. 1983.

TABLE 11-1. DOE ALTERNATIVE FUELS PROGRAM DIESEL ENGINE TESTS WITH SHALE FUELS

Contractor	Project	Fuels	Reference
Southwest Research Institute for DOE-BETC	Refining studies and engine testing for alternative highway fuels. Performance and endurance test, CLR engine	Shale DFM Shale JP-5	11-1
Southwest Research Institute for DOE-BETC	Alternative fuel in medium-speed diesel engines Shale Fuel in EMD 567B, 2-cylinder diesel engine	Shale DFM	11-2
DOE-BETC, In-house	Performance and emissions, John Deere 6466-T, farm tractor engine	Shale DFM	11-3
Energy & Environmental Research/Superior Engines	Performance and emissions, Superior 40-X-6, medium-speed diesel engine	Shale DFM, Resid blend	11-4
Marine Technology Center, Norwegian Technical Institute	Performance and emissions, Wichmann 1AX medium-speed diesel engine	Shale DFM	11-5,6
Acurex/Ricardo	Medium-speed diesel (See Section 14)	Shale resid	14-2
Cummins Engine Company Yanmar Diesel	Adiabatic engine tests (See Section 10)	Shale DFM	10-4,5
General Electric Company	Medium-speed diesel test, shale DFM	Shale DFM	11-6

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TABLE 11-2. COMPOSITION OF DIESEL FUELS EVALUATED IN CLR\* ENGINE<sup>(11-1)</sup>

Fuel	shale DFM	shale JP-5	Shale Case 2A	Shale Case 3
Sample No. AL-	9090-F	9088-F	10255-F	10256-F
<u>Composition, Volume %</u>				
Kerosene				
Petroleum	0	0	1.3	21.7
Shale JP-5/JP-8	0	100.0	17.1	10.6
Diesel				
Petroleum	0	0	23.0	21.4
Shale DFM	100.0	0	36.2	23.2
Coal SRC-II	0	0	0	0
Light Cycle Oil	0	0	22.4	23.1
HC Kerosene	0	0	0	0
Total	100.0	100.0	100.0	100.0
<u>Properties</u>				
Gravity, °API	37.9	43.6	33.0	32.9
Specific Gravity, 60°F	0.8353	0.8081	0.8602	0.8607
Distillation, D-86, °F				
IBP/5 % Recovered	402/435	354/370	369/409	373/417
10/20	452/470	373/378	427/450	432/452
30/40	482/497	384/389	472/491	467/481
50/60	508/521	396/403	508/525	497/513
70/80	533/547	412/424	543/565	531/565
90/95	563/575	442/458	599/627	595/631
EP	593	478	664	661
Recovery, %	99.0	98.5	99.0	98.0
Residue	1.0	1.5	1.0	2.0
Loss	0.0	0.0	0.0	0.0
Viscosity, cSt at 40°C	2.61(38°C)	1.38(38°C)	2.53	2.48
Pour Point °F (°C)	0(-18)		9(-13)	-2(-19)
Flash Point, °F	176	144	142	140
Hydrocarbon Type, Vol%				
Aromatics	30	22	36.9	36.1
Olefins	1	2	1.3	1.3
Saturates	69	76	61.8	62.6
Elemental Analysis, Wt%				
Carbon	86.54	85.92	86.69	86.25
Hydrogen	13.36	13.68	12.38	12.32
Oxygen	.33	.41	-	-
Nitrogen	.022	.015	-	-
Sulfur	0.004	0.005	0.55	0.52
Hydrogen/Carbon Atom Ratio	1.84	1.90	1.70	1.70
Heat of Combustion				
Gross, BTU/LB	19,537	19,688	19,470	19,520
MJ/kg	45.44	45.79	45.29	45.40
Net, BTU/LB	18,318	18,440	18,341	18,396
MJ/kg	42.6	42.89	42.66	42.79
Accel. Stability, MG/100ml	0.20	0.14	3.3	2.3
Steam Jet Gum, MG/100ml	0.0	0.0	15.3	16.5
Cetane Number	48.9	44.9	45.4	45.0

\*CLR-Cooperative Lubrication Research

TABLE 11-3. ANALYSES OF SHALE DFM USED IN EMD-567B TESTS<sup>(11-2)</sup>

Properties	Shale DFM	Petroleum No. 2-D
Specific gravity	0.835	0.819
API gravity	37.9	41.2
Distillation °C (°F)		
IBP	206 (402)	194 (381)
10%	233 (452)	211 (411)
20%	243 (470)	--
50%	264 (508)	238 (461)
90%	295 (563)	288 (550)
End Point	312 (593)	320 (608)
% Received	99	--
% Residue	1	--
% Loss	0	--
Flash point °C (°F)	80 (176)	--
Viscosity @ 37.8°C (100°F) cst	2.71	2.0
Pour point °C (°F)	-18 ( 0)	--
C, % wt	86.70	--
H, % wt	12.84	--
N, % wt	0.024	--
O, % wt	0.37	--
S, % wt	0.004	--
Heat of Combustion (BTU/lb)		
Gross	19490	19490
Net	18318	--
Cetane Number	49	50

TABLE 11-4. FUEL PROPERTIES, TEST OF SUPERIOR 40-X-6 ENGINE<sup>(11-2)</sup>

	NO. 2 DIESEL	DFM	30-70 BLEND
API GRAVITY @ 60° F	355	380	24.9
CETANE INDEX	45	53	—
POUR POINT (°F)	-15	-10	+35
FLASH POINT (°F)	153	190	198
NET HEATING VALUE (Btu/lb)	18,229	18,474	17,239
CARBON (wt. %)	86.49	86.44	87.28
HYDROGEN (wt. %)	13.07	13.41	12.37
SULFUR (wt. %)	.24	.03	.55
VISCOSITY @ 100° F (S.U.S.)	33.8	35.3	115

TABLE 11-5. PARTICULATE TEST RESULTS, SUPERIOR 40-X-6 ENGINE<sup>(11-2)</sup>

		NO. 2 DIESEL	DFM	30-70 BLEND
MASS LOADING (LBS/HR)		.490	.561	.395
ELEMENTAL ANALYSIS	% CARBON	91.8	91.5	90.9
	% ASH	1.0	1.7	20.4
PARTICLE SIZE DISTRIBUTION	> 10 $\mu$	24.73	28.3	17.3
	3-10 $\mu$	0	1.4	2.1
	1-3 $\mu$	.94	4.8	4.7
	< 1 $\mu$	74.33	65.6	75.8

TABLE 11-6. PARTICULATE PAH RESULTS,  
SUPERIOR 40-X-6 ENGINE<sup>(11-2)</sup>  
(Micrograms of PAH compound  
per liter of exhaust at  
standard conditions)

COMPOUNDS	FUELS		
	NO. 2 DIESEL	DFM	30-70 BLEND
NAPHTHALENE	.100	.038	.069
ACENAPHTHALENE	.010	.007	.009
ACENAPHTHLENE	.004	.004	—
FLUORENE	.02	.008	.01
ANTHRACENE	.017	.015	—
FLUORANTHENE	.002	.001	.001
PYRENE	.001	.002	.003
BENZO (d) PYRENE	—	—	—
BENZO (d) ANTHRACENE	—	—	.002
CHRYSENE	—	—	—
PHENANTHRENE	.006	—	.024



TABLE 11-7. PROPERTIES OF FUELS USED IN TESTS OF  
WICHMANN LAX ENGINE(11-5)

		<u>MDO</u>	<u>Shale DFM</u>
Spec. gravity at 60°F (15.6°C)	gr/cm <sup>3</sup>	0.8309	0.8065
Viscosity at 40°C	Cst	2.57	1.30
Water and sediment	%	0.01	<0.01
Sulphur	%	0.44	0
Ash	%	0.001	0
Conradson Carbon Residue	%	0.02	0.01
Cloud point	°C	-2	-52
Calculated cetane index		55	49

Boiling curve (°C):

Initial Boiling Point		172	187
5 %		190	192
10 %		210	194
20 %		219	197
30 %		234	199
40 %		252	203
50 %		265	206
60 %		280	210
70 %		296	215
80 %		313	221
90 %		335	233
95 %		350	242
Final Boiling Point		361	254
Total distilled	%	98	98
Residue	%	1.6	1.3

TABLE 11-8. ANALYSES OF DF-2, SHALE DFM, AND BLENDS (11-7)

Fuel Blends	20% Shale	35% Shale	60% Shale	80% Shale	100% Shale	100% Pet. DF-2
API grav., 60°F	40.9	40.6	39.8	39.5	38.1	41.8
Specific grav., 60°F	0.821	0.822	0.826	0.8275	0.8335	0.8165
Btu per pound	19,800	19,840	19,810	19,740	19,600	19,800
Btu per gallon	135,310	135,820	136,250	136,010	136,160	134,600
Sulfur, %	0.1	0.1	0.1	0.1	0.1	0.1
Distillation, °F						
Initial boiling point	396	397	399	403	405	394
10%	440	440	444	448	456	437
20%	463	463	467	470	476	459
30%	480	479	482	485	489	477
40%	496	496	497	498	501	494
50%	514	512	512	511	511	512
Calculated cetane index	61	60.5	59	58	55	62.5

TABLE 11-9. EXHAUST EMISSIONS FOR GENERAL ELECTRIC TWO-CYLINDER ENGINE WITH BLENDS OF DF-2 AND SHALE DFM (11-7)

Fuel	hp/cyl	rpm	NO <sub>x</sub> g/hp-hr	CO g/hp-hr	HC g/hp-hr	Smoke Bosch No.
Pet. No. 2*	206	1050	9.2	3.4	1.0	0.9
20% shale	206	1050	8.6	3.7	0.9	1.1
30% shale	206	1050	10.5	3.5**	0.8**	0.8**
50% shale	206	1050	9.9	3.2**	0.8**	0.8**
100% shale	206	1050	9.2	3.5	0.8	0.7
Pet. No. 2*	100	879	12	2.7	1.2	0.6
20% shale	100	879	11.5	3.8	1.1	1.2
30% shale	100	879	13.7	2.6**	0.7**	0.6**
50% shale	100	879	13.9	2.6**	0.7**	0.6**
100% shale	100	879	13.4	4.6	0.9	0.8
Pet. No. 2*	22	535	15	1.9	2.1	0.4
20% shale	22	535	17.3	2.2	1.5	0.4
30% shale	22	535	12.7	2.5**	1.5**	0.6**
50% shale	20	535	13.6	1.7**	1.5**	0.2**
100% shale	23	535	17.6	1.9	1.2	0.4

\* Average three runs.

\*\* Values corrected to baseline run immediately preceding test runs.

TABLE 11-10. PISTON TEMPERATURES, F, FOR GENERAL ELECTRIC TESTS OF TWO-CYLINDER ENGINE WITH SHALE DFM BLENDS<sup>(11-7)</sup>

Fuel Blends	Piston Intake			Piston Exhaust			Valve Intake	Valve Exhaust
	Crown	Above Top Ring	Below Top Ring	Crown	Above Top Ring	Below Top Ring		
Pet. No. 2 avg. (3)	412	249	231	450	285	245	570	826
30% shale	412	253	237	455	289	250	573	772
50% shale	413	254	237	455	289	251	571	777
100% shale	403	252	234	448	287	248	566	770
50% shale - 50% resid.	413	238	220	444	282	241	598	940
50% Pet. - 50% resid.	407	237	221	445	283	240	603	937

TABLE 11-11. PEAK CYLINDER PRESSURES, PSIA, FOR GENERAL ELECTRIC TESTS OF TWO-CYLINDER ENGINE WITH SHALE DFM BLENDS<sup>(11-7)</sup>

Fuel Blends	hp/Cyl	rpm	Cylinder Pressure	hp/cyl	rpm	Cylinder Pressure	hp/cyl	rpm	Cylinder Pressure
Pet. No. 2 avg. (3)	206	1050	1705	100	879	1143	20	535	738
20% shale	206	1050	1680	100	879	1160	20	535	740
30% shale	206	1050	1770	100	879	1120	20	535	700
50% shale	206	1050	1770	100	879	1130	20	535	710
100% shale	206	1050	1680	100	879	1160	20	535	780
50% shale - 50% resid.	206	1050	1830	100	879	1160	20	535	740
50% Pet. - 50% resid.	206	1050	1810	100	879	1160	20	535	750

TABLE 11-12. CHANGES IN LUBRICATING OIL PROPERTIES FOR FUEL BLENDS, FOR GENERAL ELECTRIC TESTS OF EIGHT-CYLINDER ENGINE<sup>(11-7)</sup>

Fuels	First Pet. No. 2	CDL + Pet. No. 2	Shale Pet. No. 2	Shale + Pet. Resid.	Pet. No. 2 + Pet. Resid.	Second Pet. No. 2
<i>Property Change Per 100 H.</i>						
Viscosity Increase at 100 °F, SSU	31.5	18.6	28	41	23	25.5
Wt% pentane insol. increase	0.33	0.44	0.2	0.75	0.34	0.19
Total base no. decrease (ASTM 664)	1.3	1.8	2	2.3	2.0	1.1
Iron increase, PPM	1.3	4.4	5	3.3	4.1	2
Copper increase, PPM	1.3	1.6	0	0	0	0
Lead increase, PPM	1.3	0.5	9	0	0	*3.4

\* No. 2 fuel for second run contained 14 PPM lead and low flash (gasoline contamination)

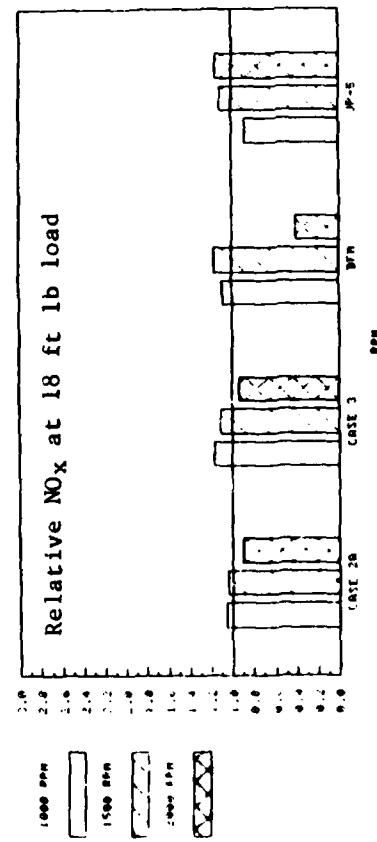
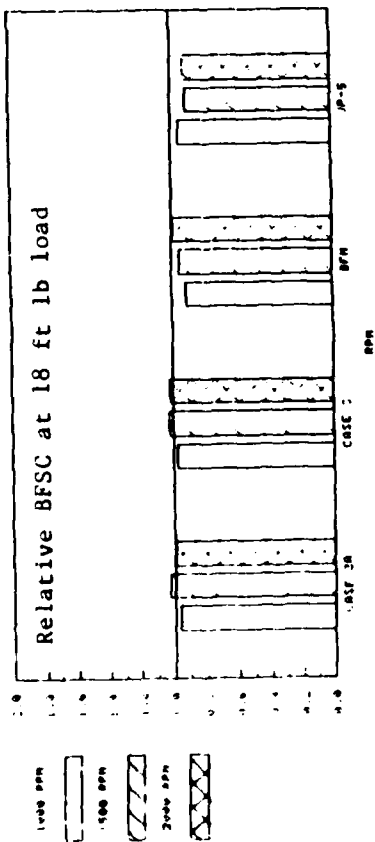
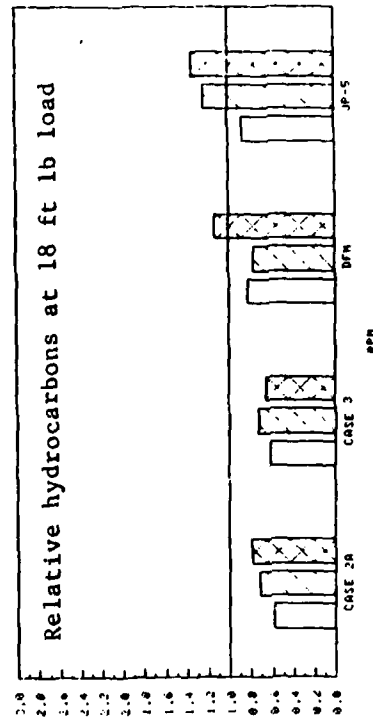
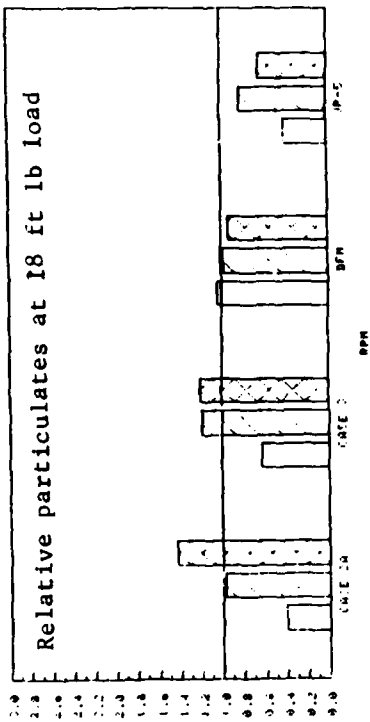
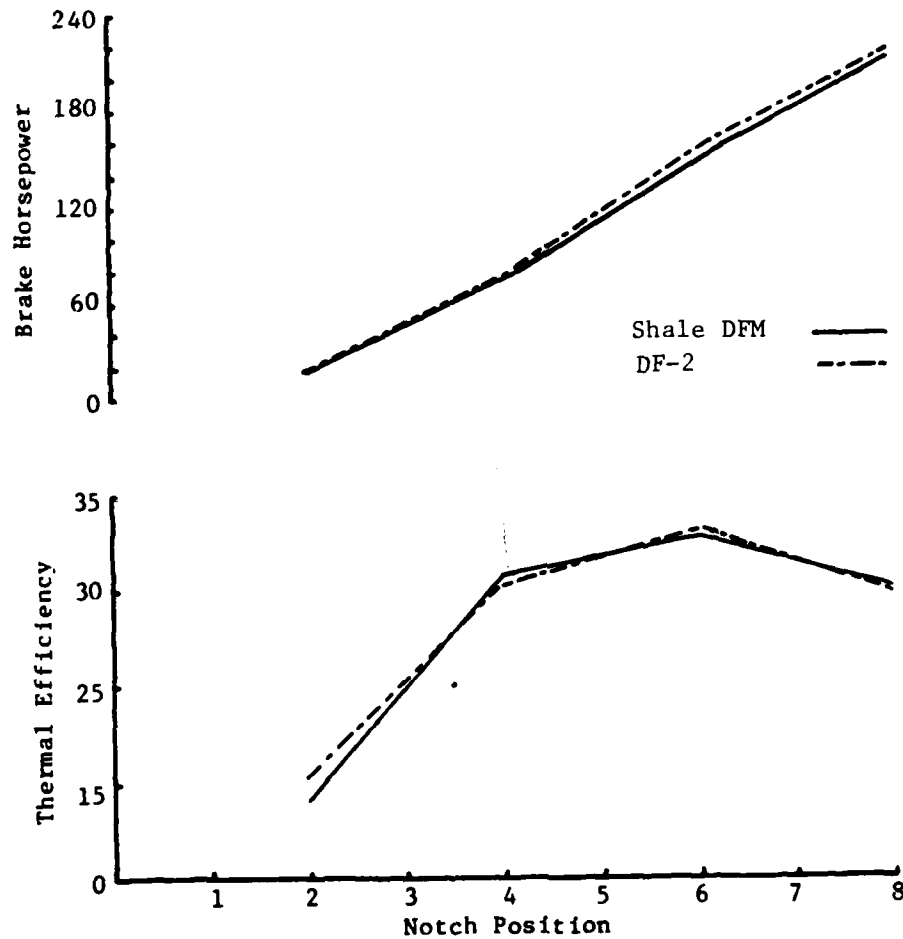


FIGURE 11-1. RELATIVE EMISSIONS FROM CLR ENGINE WITH FOUR FUELS (11-1)

Test Engine: EMD 2-567B

FIGURE 11-2. SHALE DFM PERFORMANCE CURVES,  
EMD 2-567B ENGINE (11-2)

Test Engine: EMD 2-567B

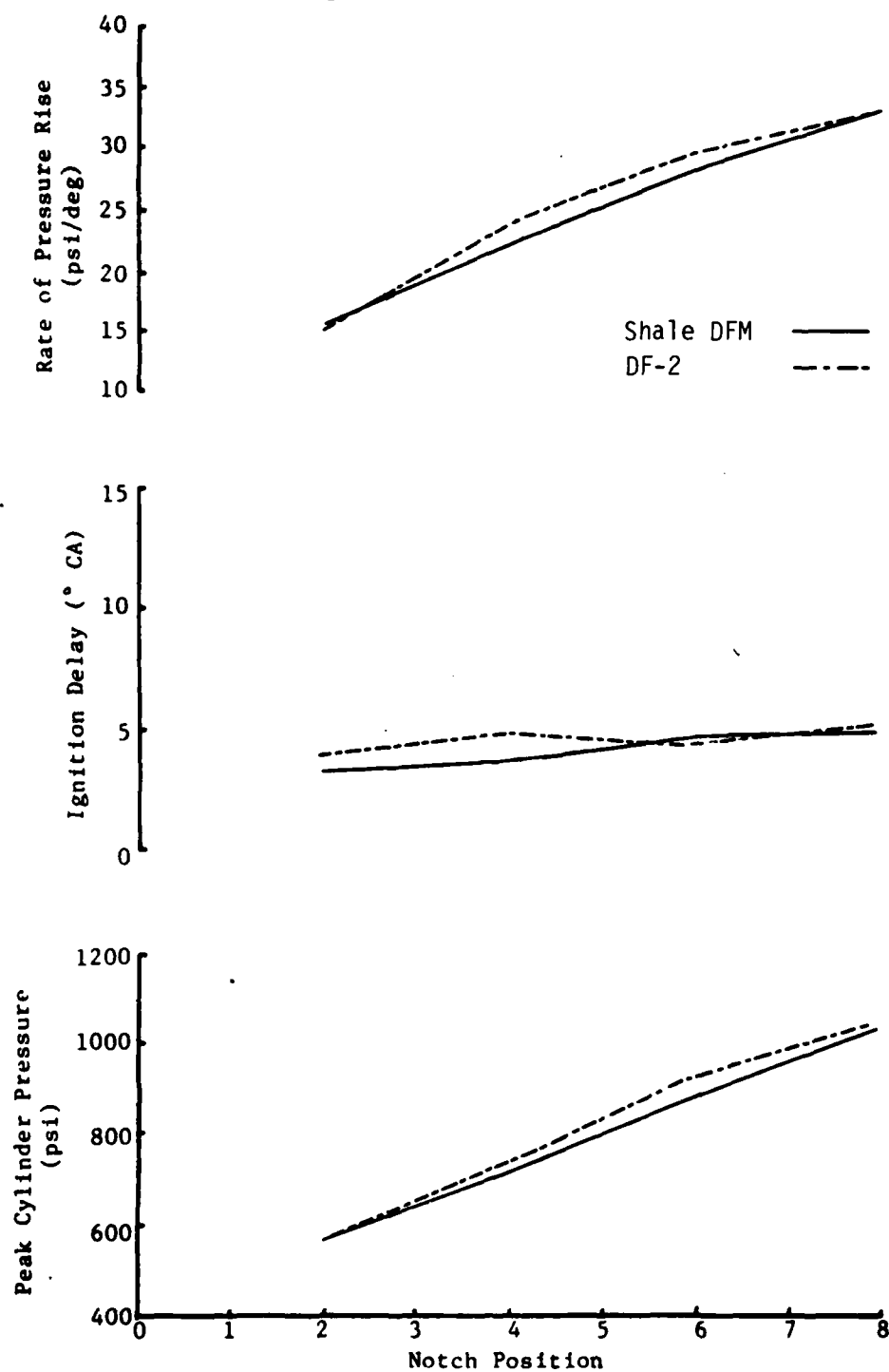


FIGURE 11-3. SHALE DFM COMBUSTION CHARACTERISTICS, EMD 2-567B ENGINE(11-1)

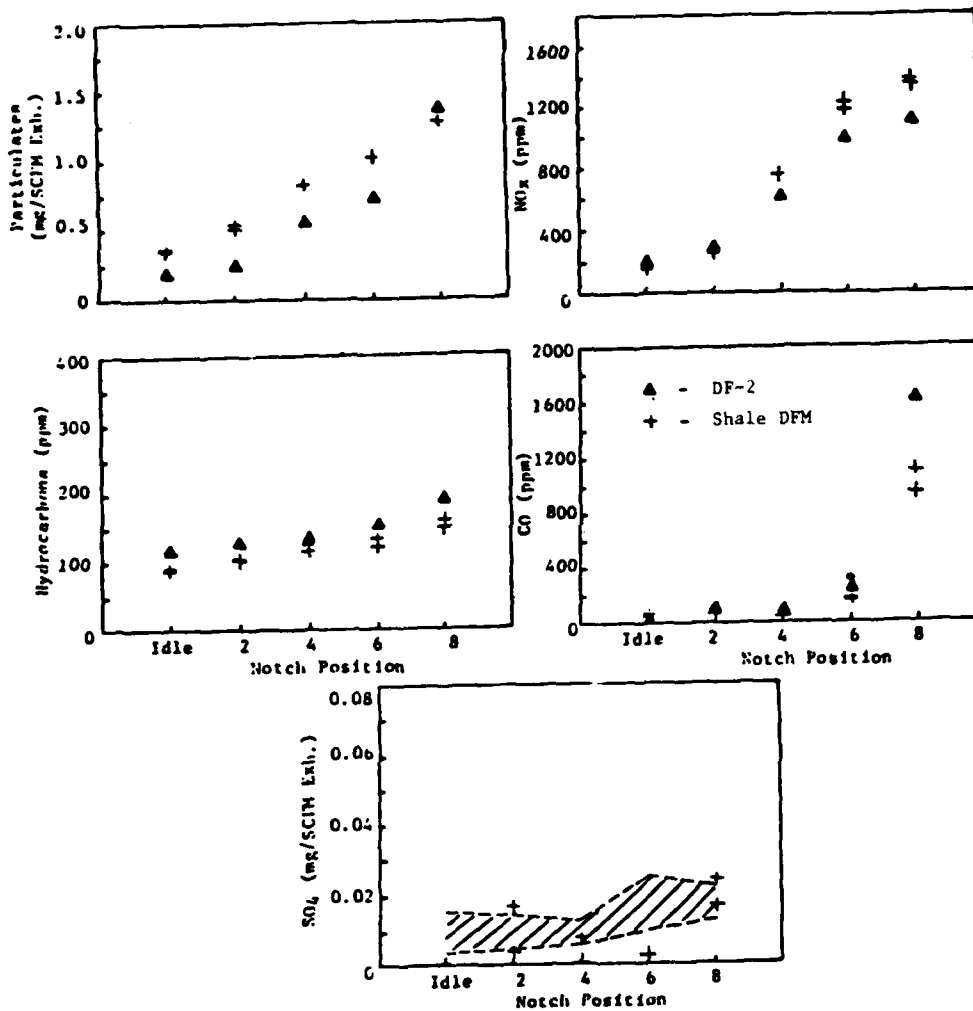


FIGURE 11-4. SHALE DFM EMISSIONS,  
EMD 567B ENGINE(11-2)

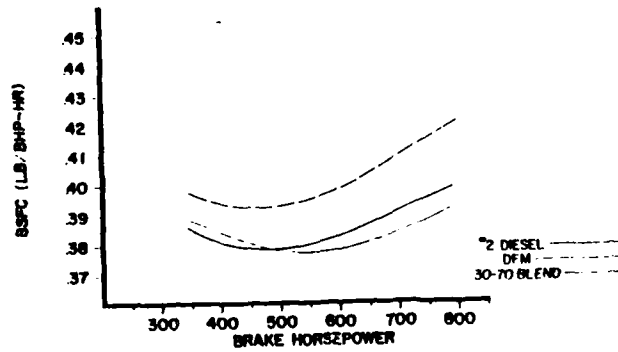


FIGURE 11-5. BSFC VS BRAKE HORSEPOWER FOR AN ENGINE SPEED OF 900 RPM, SUPERIOR 40-X-6 ENGINE(11-4)

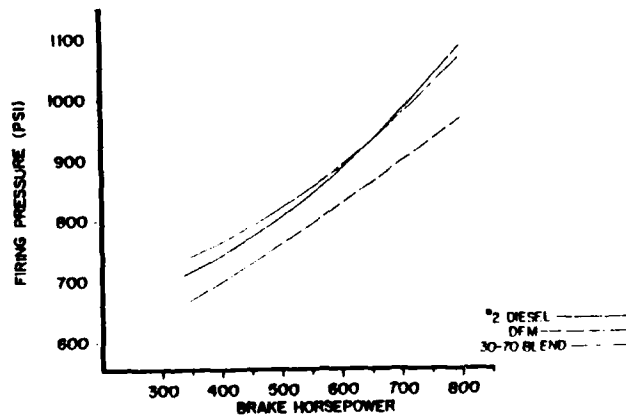


FIGURE 11-6. MAXIMUM FIRING PRESSURE VS BRAKE HORSEPOWER FOR AN ENGINE SPEED OF 900 RPM, SUPERIOR 40-X-6 ENGINE(11-4)



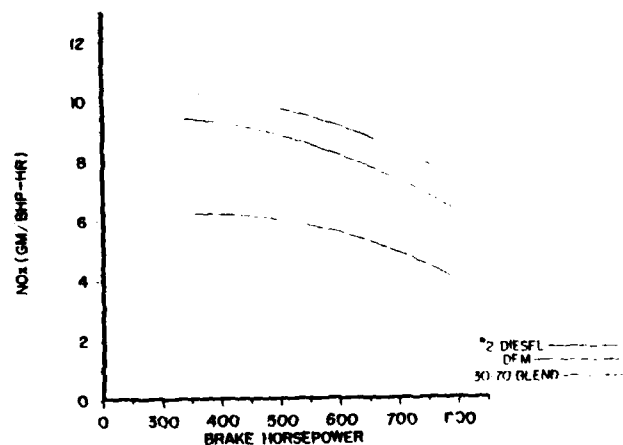


FIGURE 11-7.  $\text{NO}_x$  VS BRAKE HORSEPOWER FOR AN ENGINE SPEED OF 900 RPM, SUPERIOR 40-X-6 ENGINE(11-4)

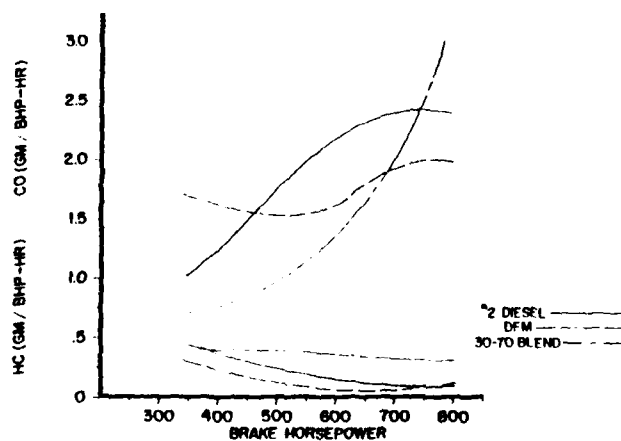


FIGURE 11-8. HC AND CO VS BRAKE HORSEPOWER FOR AN ENGINE SPEED OF 900 RPM, SUPERIOR 40-X-6 ENGINE(11-4)

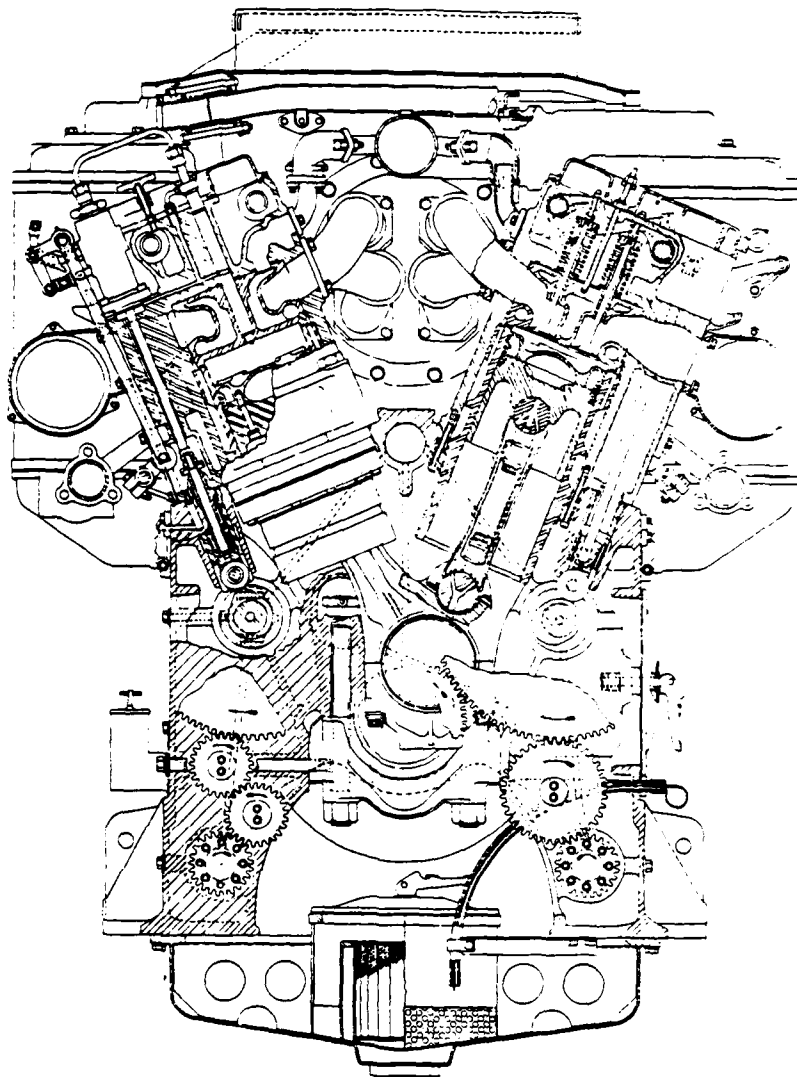


FIGURE 11-9. CROSS SECTION OF GENERAL ELECTRIC TYPE FDL  
LOCOMOTIVE DIESEL ENGINE<sup>(11-7)</sup>

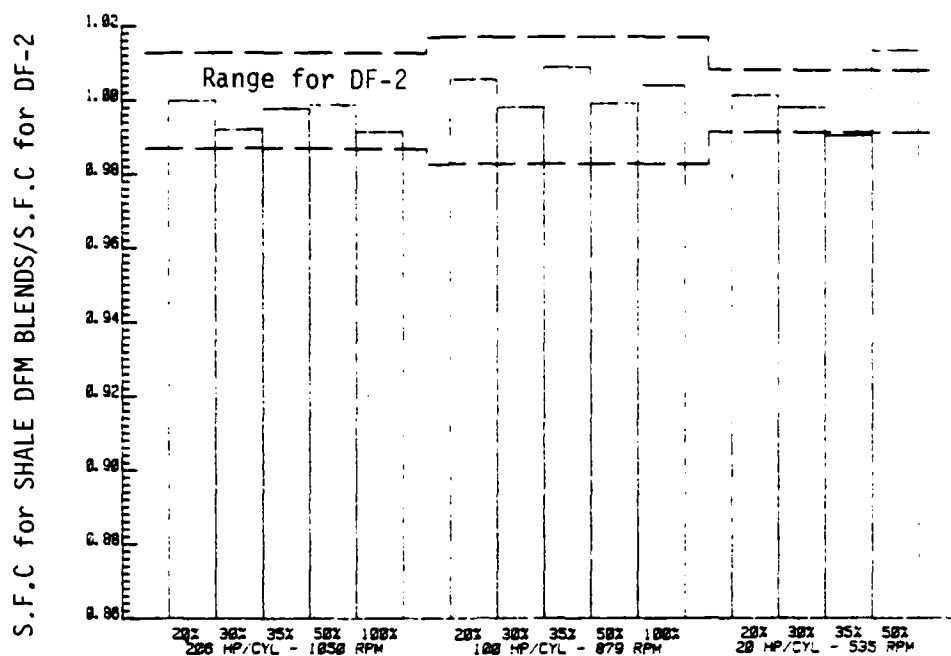


FIGURE 11-10. RATIO OF SPECIFIC FUEL CONSUMPTION WITH SHALE DFM BLENDS TO THAT FOR DF-2. GE TYPE FDL TWO-CYLINDER ENGINE (11-7)

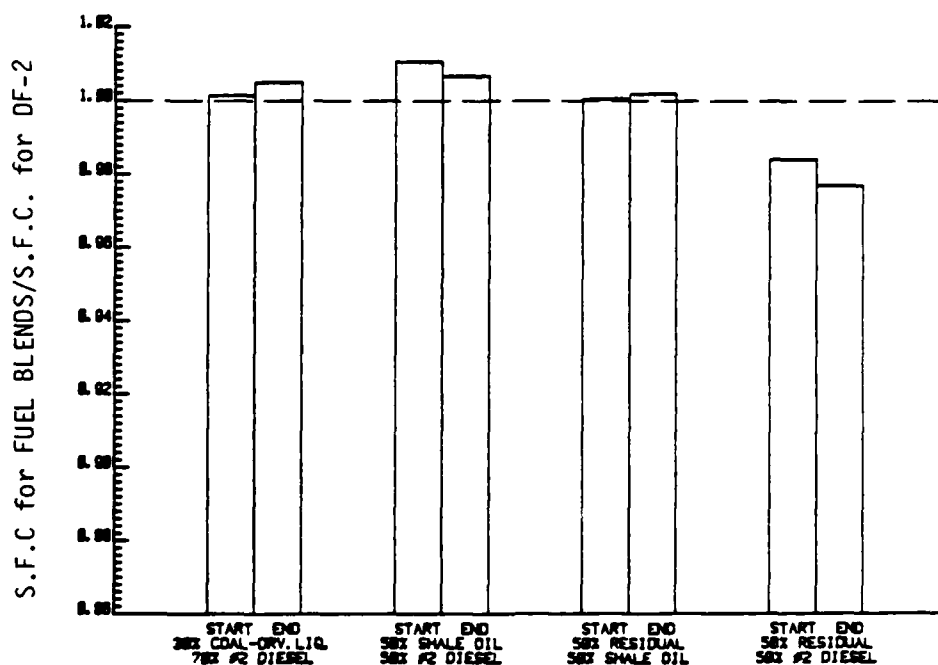


FIGURE 11-11. RATIO OF SPECIFIC FUEL CONSUMPTION WITH VARIOUS FUEL BLENDS TO THAT FOR DF-2. GE TYPE FDL EIGHT-CYLINDER ENGINE. VALUES BEFORE AND AFTER 100-HOUR ENDURANCE TESTS (11-7)

## 12. EPA TESTS OF SHALE-DERIVED FUELS IN LIGHT-DUTY DIESEL ENGINES

### Introduction

The Environmental Protection Agency (EPA) sponsored three investigations of shale-derived fuels in light-duty diesel engines. One of the tests was performed in-house at EPA's Mobile Source Emissions Research Branch at Research Triangle Park, NC(12-1). The others were performed under contract to EPA by the U. S. Department of Transportation/Transportation Systems Center (DOT/TSC), Cambridge, MA(12-2) and Southwest Research Institute (SWRI), San Antonio, Texas(12-3,4). The objective of all the tests was to assess the performance of diesel-powered automobiles while burning shale-derived fuels compared to their performance when burning petroleum diesel fuel.

Table 12-1 lists the automobiles and fuels evaluated by each of the participants in the EPA program. A Volkswagen Rabbit was tested by each organization. EPA and SWRI evaluated naturally aspirated Rabbit vehicles, while DOT/TSC tested a prototype turbocharged Rabbit diesel. EPA also tested an Oldsmobile V-8 diesel. All three organizations tested shale DFM in their vehicles. SWRI also evaluated shale JP-5.

These tests were performed in keeping with EPA's mission of qualifying light- and medium-duty transportation engines in terms of their performance and emissions characteristics. The evaluation of fuels from alternative feedstocks in transportation engines becomes increasingly important as the time at which they will become commercially available approaches.

An additional evaluation of shale fuels in automotive diesel engines was performed under private sponsorship by General Motors. That evaluation, reported in Section 13 of this report, consisted of driving two vehicles 30,000 miles each burning only shale DFM.

The balance of this section consists of a description of the vehicles tested, summaries of the procedures and results observed in each of the three evaluations and a statement of the conclusions derived from the investigations.

### Vehicle Descriptions

Table 12-2 presents descriptions of the four vehicles tested. EPA evaluated two naturally aspirated diesel engines, an Oldsmobile and Volkswagen Rabbit. Both were in 1980 model year vehicles. The Oldsmobile produced 105 hp with a displacement of 5.7 liters, while the Volkswagen developed 36 hp with a displacement of 1.5 liters. The Oldsmobile was equipped with a three-speed automatic transmission. The Volkswagen transmission was a four-speed manual.

The vehicle tested by SWRI was virtually identical to the Volkswagen tested by EPA except that the SWRI vehicle had a five-speed transmission. In contrast, the Rabbit tested by DOT/TSC was a turbo-charged prototype not commercially available in the United States. The inertia test weights of the three Volkswagens were all 1020 kg (2250 lb), while the Oldsmobile weighed 2050 kg (4520 lb).

#### EPA Tests of Shale DFM in Oldsmobile and Volkswagen Rabbit(12-1)

The objective of the EPA tests was to determine the fuel sensitivity of two automotive diesel engines by measuring their performance over six driving schedules while burning three petroleum distillates and shale DFM. Fuel economy and emissions of hydrocarbons, CO, NO<sub>x</sub> and particulates were measured. Particulates were analyzed for the presence of polynuclear aromatic species (PNAs) and were tested for mutagenic activity.

#### Procedure

The vehicles were placed on chassis dynamometers and tested by varying engine speed and load according to six standardized test cycles. Four fuels were evaluated in each vehicle.

Table 12-3 summarizes the properties of the four fuels tested. The reference fuel was prepared by Phillips Chemical Company and distributed by the Department of Energy as a national control fuel for diesel emissions tests. The two other petroleum derivatives were samples of commercially available fuels. The petroleum fuels are similar in all important respects. The shale DFM is less dense and has a higher cetane number than the petroleum fuels, characteristics of a highly refined product.

Table 12-4 describes the six test cycles over which each vehicle was evaluated. Fuel economy and emissions were monitored according to standardized and well-documented procedures. Particulates were analyzed for total mass, soluble organic fraction (SOF) and trace metals. In addition, the SOF was evaluated for the presence of various PNAs and was assayed for mutagenic activity.

#### Results

Vehicle performance was insensitive to fuel type for nearly all variables monitored. While individual test results for different fuels often varied significantly, few overall trends could be discerned when viewing the data for both vehicles over the six driving cycles.

Tables 12-5 and 12-6 summarize the gaseous emissions and fuel economy for the Volkswagen and Oldsmobile, respectively. The emissions data are essentially trendless with fuel type. Fuel economy while burning shale DFM was typically lower than that for the petroleum distillates.

Tables 12-7 and 12-8 include the total mass of particulates collected and the SOF (in dichloromethane, DCM) for the two vehicles. The shale DFM often produced less particulates than the petroleum distillates, particularly in the Oldsmobile. However, in eleven of the twelve tests the SOF of the shale DFM exceeded that of the other three fuels. The soluble organics present in particulates often contain PNAs that are suspected carcinogens.

Table 12-9 contains mutagenic bioassay results that only partially reflect the higher SOF exhibited by the shale DFM particulates. The Volkswagen exhaust emissions produced significantly more revertants while burning shale DFM than the petroleum distillates. However, the shale DFM emissions from the Oldsmobile were relatively benign in terms of mutagenicity. These results as well as most others in this study indicate that the shale DFM is nearly indistinguishable from petroleum distillates as an automotive diesel fuel.

#### DOT/TSC Test of Shale DFM in a Turbocharged Volkswagen Rabbit(12-2)

The primary objectives of this investigation were to characterize the fuel economy and emissions for a turbocharged Volkswagen Rabbit burning conventional diesel fuel and to collect a large quantity of particulates for analysis under EPA's Diesel Health Effects Research Program. A secondary objective was to measure fuel economy and emissions while burning shale-derived DFM and compare the results to those achieved with conventional fuel.

#### Procedure

Fuel analyses were performed on both the shale-derived DFM and the reference fuel, EPA-ESRL, a standard used widely in the Diesel Particulate Health Effects Research Program. Fuel economy and emissions tests were performed with the vehicle mounted on a chassis dynamometer. Engine speed and load were varied according to four standardized EPA test cycles: the Federal Test Procedure, Highway Fuel Economy Test, New York City Cycle and the Congested Urban Expressway Cycle. (see Table 12-4) Pollutant species consisting of unburned hydrocarbons (HC), CO, NO<sub>x</sub> and particulates were monitored and are reported in grams/mile.

Table 12-10 summarizes the fuel analyses for the shale DFM and the reference fuel. The only significant differences between the two fuels are the higher cetane number and higher hydrogen content of the shale DFM.

## Results

Figure 12-1 and 12-2 present the results of burning shale DFM in the turbocharged Rabbit. Fuel economy and emissions figures are presented directly in Figure 12-1, while the entries in Figure 12-2 consist of the shale DFM results relative to those achieved with the reference fuel. HC and CO emissions were significantly lower for shale DFM than for the reference fuel; the authors attribute these results to the shale DFM's higher cetane number. Particulate and NO<sub>x</sub> emissions, on the other hand, were higher for the shale DFM. Particulate emissions are reported to vary with hydrogen content, a trend that is borne out here. NO<sub>x</sub> emissions often correlate with fuel aromatic content. Unfortunately, this parameter was not measured, precluding any comparison. Fuel economy results were quite similar for the two fuels over all four test cycles.

### SWRI Test of Shale DFM and JP-5 in a Volkswagen Rabbit(12-3,4)

The objective of this investigation was to evaluate the performance of a 1980 Volkswagen Rabbit while burning distillates and blends derived from petroleum, oil shale and coal. In contrast to the EPA and DOT/TSC studies, SWRI tested nine separate fuels including shale JP-5 and shale DFM. Fuel economy and emissions were measured and particulates were evaluated for mutagenic potential via bioassay.

## Procedure

A Volkswagen Rabbit nearly identical to the vehicle tested by EPA was operated on a chassis dynamometer over two test cycles, the Federal Test Procedure and the Highway Fuel Economy Test. Fuel economy and emissions measurements were made while burning nine fuel types, including shale DFM and shale JP-5.

Table 12-11 presents extensive analyses of each of the fuels. The base fuel is a so-called "national average" petroleum-derived No. 2 diesel fuel. In addition to the two shale distillates, six blends containing coal-derived liquids were also tested. The unblended coal liquids were not acceptable as automotive diesel fuels due to low cetane number.

Emissions were monitored for regulated species (HC, CO, NO<sub>x</sub>) as well as aldehydes, phenols and odor. Particulates were monitored for total mass, size distribution and composition. Particle composition was characterized in terms of trace elements and major species (carbon and hydrogen), soluble organic fraction, fractionation of the soluble organics and evaluation of mutagenic potential via bioassay.

## Results

Figures 12-3 and 12-4 present the regulated gaseous emissions measured for 8 of the 9 fuels during the Federal Test Procedure and the Highway Fuel Economy Test. In Figures 12-3 through 12-6 the terminology "Shale Diesel Marine" is used for shale DFM, and "Paraho JP-5" is used for shale JP-5. The blend of 35 percent SRC-II and 65 percent petroleum diesel fuel yielded high emissions levels that plugged the sampling system, precluding further testing of this fuel. The two shale distillates produced higher gaseous emissions levels than the base DF-2. Shale JP-5 emissions were typically higher than shale DFM emissions. Among the non-regulated species (aldehydes, phenols and odor), the only noteworthy observation was the negligible phenol emission rate of shale JP-5 relative to that of shale DFM and the base DF-2.

Figure 12-5 summarizes the fuel consumption exhibited by the test vehicle while burning the various fuels over the Federal Test Procedure (FTP) and Highway Fuel Economy Test (HFET) cycles. Fuel consumption rates for the two shale distillates were nearly identical and exceeded the rate for the base DF-2 over both cycles.

Figure 12-6 presents the particulate emissions for the FTP and HFET cycles. Shale JP-5 and the base DF-2 exhibited nearly identical levels, while shale DFM yielded slightly more particulate matter during both cycles.

Table 12-12 summarizes the mutagenicity bioassay results for the eight fuels tested. Both shale derivatives were found to be somewhat more mutagenic than the base DF-2. Between the two shale liquids, the DFM was more mutagenic than the JP-5. These trends correlate with benzo-a-pyrene (BaP) emissions recorded during the same tests. However, the most highly mutagenic emissions were derived from the 25 percent SRC-II blend, which exhibited the second-lowest BaP emissions of all fuels tested. Thus, no direct correlation was demonstrated between mutagenicity and the presence of this suspected carcinogen.

## Conclusions

Shale DFM and shale JP-5 were tested in automotive diesel engines in three independent studies under EPA sponsorship. One study was performed in house at EPA's Mobile Source Emissions Research Branch. The others were performed by Southwest Research Institute (SWRI) and the Department of Transportation/Transportation Systems Center (DOT/TSC).

EPA compared shale DFM with three petroleum-based diesel fuels in dynamometer testing with 1980 Oldsmobile and Volkswagen Rabbit automobiles. Engine speed and load were varied according to six standardized driving cycles. The results included HC, CO, NO<sub>x</sub> and



particulate emissions, fuel economy, particulate composition and mutagenic activity of the particulate soluble organic fraction.

Differences between the shale DFM and the petroleum distillates were generally slight and often trendless when considering the full matrix of two vehicles and six cycles. The results therefore suggest that shale DFM is an acceptable substitute for petroleum-derived diesel fuels in automotive engines.

Shale DFM was tested by DOT/TSC in a prototype turbocharged Volkswagen Rabbit diesel. Engine speed and load were varied to simulate four standard test cycles. Fuel economy with shale DFM was similar to that achieved with a reference fuel, EPA-ESRL. Particulate and NO<sub>x</sub> emissions with shale DFM were higher, while HC and CO levels were lower. On the basis of these results, shale DFM appears to be an acceptable fuel for small turbocharged automotive diesel engines.

Southwest Research Institute burned shale DFM and JP-5 in a 1980 Volkswagen Rabbit. A petroleum-based national average DF-2 fuel and six blends of DF-2 with coal liquids were also tested. The vehicle, mounted on a chassis dynamometer, was operated according to the Federal Test Procedure and the Highway Fuel Economy Test cycles. The variables of interest were largely the same as those observed by EPA. The shale liquids produced higher levels of regulated gaseous emissions than the DF-2. Fuel consumption rates were also higher for the shale liquids. Particulate emissions for shale JP-5 and the DF-2 fuel were nearly identical, and were slightly less than those observed with shale DFM. The shale derivatives were more mutagenic than the DF-2 fuel. SWRI's results indicate that shale DFM and shale JP-5 are slightly inferior to the DF-2 fuel tested in several categories. Nevertheless, the differences noted between the shale fuels and the DF-2 are not of sufficient consequence to preclude the use of shale fuels in automotive diesels. Rather, the results suggest that suitably refined shale liquids can be substituted for conventional petroleum transportation fuels with no worse than slight increases in fuel consumption and emissions levels.

#### References

- 12-1. Gabele, P. A., Zweidinger, R. and Black, F., "Passenger Car Exhaust Emission Patterns: Petroleum and Oil Shale Derived Diesel Fuels", SAE Paper 820770, presented at Passenger Car Meeting, Troy, Michigan, June 7-10, 1982.
- 12-2. Walter, R. A., Quayle, S. S., and Sturm, J. C., "Fuel Economy and Exhaust Emissions Characteristics of a Diesel Vehicle: Results of the Prototype Volkswagen 1.5-Liter Turbocharged Rabbit Tests", DOT-TSC-RSPA-82-2, Transportation Systems Center, Cambridge, Massachusetts, October 1981.

- 12-3. Bykowoki, B. B., "Characterization of Diesel Emissions From Operation of a Light-Duty Diesel Vehicle on Alternate Source Diesel Fuels", EPA-460/3-82-002, Southwest Research Institute, San Antonio, Texas, November 1981.
- 12-4. Bykowski, B. B. and Baines, T. M., "Effects of Alternate Source Diesel Fuels on Light-Duty Diesel Emissions", SAE Paper 820771, presented at Passenger Car Meeting, Troy, Michigan, June 7-10, 1982.

TABLE 12-1 PARTICIPANTS IN EPA SHALE FUEL EVALUATIONS

<u>Vehicle</u>	<u>Evaluating Organization</u>	<u>Fuel</u>	<u>Reference</u>
1980 Oldsmobile V-8 Diesel	EPA/Mobile Source Emissions Branch	Shale DFM Shale DFM	12-1
1980 Volkswagen Rabbit	EPA/Mobile Source Emissions Branch	Shale DFM	12-1
Prototype Turbo-charged Volkswagen Diesel	Department of Transportation/Transportation Systems Center	Shale DFM	12-2
1980 Volkswagen Rabbit	Southwest Research Institute	Shale DFM and JP-5	12-3, 4

TABLE 12-2 DESCRIPTIONS OF VEHICLES USED FOR EPA FUEL EVALUATIONS

Evaluator	EPA	EPA	DOT/TSC	SWRI
Model	Oldsmobile	VW Rabbit	VW Rabbit	VW Rabbit
Model Year	1980	1980	prototype	1980
Cylinders	8	4	4	4
Displacement, liters	5.7	1.5	1.5	1.5
Compression Ratio	23:1	23:1	23.5:1	23:1
Power Output, kw (hp)	78 (105)	36 (48)	51 (70)	36 (48)
Aspiration	natural	natural	turbocharged	natural
Rated Speed, rpm	3200	5000	4800	5000
Vehicle Weight, kg (lb)	2050 (4520)	1020 (2250)	1020 (2250)	1020 (2250)
Combustion Chamber	prechamber	prechamber	prechamber	prechamber
Transmission Type	automatic	manual	manual	manual
Speeds	3	4	4	5

TABLE 12-3. PROPERTIES OF FUELS TESTED IN 1980 VOLKSWAGEN  
AND OLDSMOBILE DIESEL VEHICLES BY EPA<sup>(12-1)</sup>

SOURCE	OIL SHALE	AMOCO	UNION 76	REFERENCE *
FUEL CODE	DFM-F		RTP-100	
GRAVITY, API	38.8	33.9	35.2	35.0
DENSITY, g/ml	0.8359	0.8551	0.8484	0.8498
SULFUR, wt. %	0.02	0.18	0.30	0.34
CETANE NUMBER	57.0	46.0	48.0	47.8
DISTILLATION TEMP., °F				
IBP	395	357	360	372
10%	450	428	424	427
50%	503	509	504	504
90%	553	597	588	568
EP	574	638	638	600
FIA, %				
AROMATICS	34.3	39.9	—	30.5
OLEFINS	4.1	2.0	—	5.0
SATURATES	61.6	58.1	—	64.5
CARBON, wt. %	84.08	86.8	86.6	85.6
HYDROGEN, wt. %	14.96	12.8	12.9	14.0
NITROGEN, wt. %	<0.01	—	—	—
VISCOSITY, CS @ 100°F	2.73	2.81	2.69	2.57

\* Reference petroleum DF-2

TABLE 12-4. STANDARDIZED DRIVING CYCLES EMPLOYED BY EPA<sup>(12-1)</sup>

TEST CYCLE	COLD START	AVG. SPEED	STOPS PER MI.	TOTAL DISTANCE (MI.)	DURATION (min)	% IDLE
FTP	YES	21.3	2.40	11.1	31.3	19.0
HFET	NO	48.2	0.20	10.2	12.7	0.8
CUE	NO	34.8	0.15	13.5	23.3	2.6
NYCC	NO	7.1	9.32	1.2	10.0	40.2
SC	NO	33.8	0.86	7.0	12.4	—
45 S.S.	NO	45.0	0	7.5	10.0	0.0

FTP--Federal Test Procedure; HFET--Highway Fuel Economy Test;  
CUE--Congested Urban Expressway; NYCC--New York City Cycle;  
SC--Special Cycle; 45 S.S.--45 mph Steady State

TABLE 12-5. VOLKSWAGEN GASEOUS EMISSIONS AND FUEL ECONOMY  
RECORDED IN EPA TESTS<sup>(12-1)</sup>

Emission	Fuel	FTP	HFET	CUE	NYCC	Special Cycle	45 SS
THC, g/mi.	Amoco	0.26(±.01)	0.23(±.02)	0.25(±.02)	0.45(±.03)	0.33(±.06)	0.14(±.02)
	Ref.	0.26(±.02)	0.23(±.04)	0.24(±.02)	0.46(±.09)	0.27(±.05)	0.15(±.01)
	RTP-100	0.23(±.02)	0.24(±.02)	0.24(±.06)	0.40(±.11)	0.28(±.06)	0.16(±.02)
	Shale	0.22(±.02)	0.23(±.01)	0.23(±.02)	0.41(±.12)	0.34(±.09)	0.15(±.02)
CO, g/mi	Amoco	1.25(±.03)	1.24(±.09)	1.25(±.11)	1.90(±.10)	1.37(±.32)	0.86(±.11)
	Ref.	1.18(±.06)	1.10(±.13)	1.11(±.14)	1.86(±.15)	1.21(±.07)	0.80(±.03)
	RTP-100	1.11(±.06)	1.15(±.10)	1.16(±.05)	1.71(±.32)	1.30(±.14)	0.85(±.08)
	Shale	1.19(±.05)	1.21(±.10)	1.17(±.08)	1.94(±.23)	1.35(±.04)	0.87(±.05)
NO, g/mi	Amoco	0.88(±.05)	0.85(±.03)	0.81(±.04)	1.31(±.05)	0.77(±.02)	0.76(±.12)
	Ref.	0.90(±.06)	0.88(±.03)	0.79(±.04)	1.39(±.04)	0.83(±.04)	0.76(±.05)
	RTP-100	0.81(±.02)	0.87(±.04)	0.82(±.05)	1.35(±.09)	0.74(±.09)	0.71(±.06)
	Shale	0.86(±.08)	0.89(±.08)	0.79(±.07)	1.37(±.01)	0.78(±.06)	0.75(±.03)
Fuel Economy, MPG	Amoco	46.9(±3.3)	49.4(±.01)	52.8(±.5)	35.1(±2.1)	53.8(±1.1)	60.0(±0.0)
	Ref.	46.6(±2.3)	49.0(±2.0)	51.7(±2.1)	33.6(±0.7)	52.3(±1.6)	59.3(±1.8)
	RTP-100	47.6(±1.4)	48.7(±1.5)	51.4(±1.5)	32.6(±1.0)	51.0(±2.6)	59.5(±2.4)
	Shale	46.1(±2.3)	47.7(±1.0)	50.8(±3.0)	31.9(±2.6)	50.5(±0.5)	57.8(±1.7)

TABLE 12-6. OLDSMOBILE GASEOUS EMISSIONS AND FUEL ECONOMY  
RECORDED IN EPA TESTS<sup>(12-1)</sup>

Emissions	Fuel	Driving Cycle				Special Cycle	45 SS
		FTP	HFET	CUE	NYCC		
THC, g/mi	Amoco	0.24(±.02)	0.09(±.01)	0.11(±.01)	0.55(±.08)	0.14(±.01)	0.06(±.01)
	Ref.	0.24(±.03)	0.09(±.01)	0.13(±.01)	0.53(±.03)	0.13(±.01)	0.06(±.01)
	RTP-100	0.22(±.01)	0.07(±.01)	0.10(±.02)	0.46(±.11)	0.13(±.08)	0.04(±.02)
	Shale	0.23(±.05)	0.07(±.01)	0.11(±.02)	0.51(±.11)	0.11(±.01)	0.05(±.01)
CO, g/mi	Amoco	1.37(±.08)	.77(±.06)	1.01(±.08)	3.18(±.32)	1.22(±.09)	.53(±.09)
	Ref.	1.28(±.06)	.71(±.07)	.94(±.09)	3.06(±.52)	1.16(±.12)	.54(±.07)
	RTP-100	1.33(±.04)	.70(±.05)	1.05(±.11)	2.67(±.13)	1.23(±.15)	.47(±.01)
	Shale	1.44(±.20)	.73(±.11)	.94(±.06)	3.01(±.21)	1.14(±.10)	.57(±.10)
NO, g/mi	Amoco	1.12(±.04)	.77(±.05)	.87(±.04)	2.77(±.14)	0.96(±.06)	.76(±.11)
	Ref.	1.02(±.05)	.72(±.04)	.77(±.10)	2.42(±.34)	.75(±.13)	.61(±.08)
	RTP-100	1.00(±.03)	.74(±.05)	.79(±.07)	2.45(±.34)	.84(±.06)	.64(±.08)
	Shale	0.98(±.10)	.65(±.06)	.74(±.03)	2.41(±.22)	.79(±.07)	.63(±.05)
Fuel Economy, MPG	Amoco	21.8(±3.3)	31.9(±1.6)	28.9(±2.3)	11.0(±0.4)	26.0(±1.0)	42.4(±3.4)
	Ref.	21.7(±0.4)	32.3(±0.6)	29.3(±0.9)	11.3(±1.6)	25.3(±1.5)	41.2(±2.1)
	RTP-100	21.9(±0.4)	32.6(±0.7)	29.3(±0.9)	11.9(±0.0)	26.5(±0.3)	40.5(±2.8)
	Shale	22.5(±2.7)	31.3(±1.3)	28.3(±1.1)	10.9(±0.5)	25.6(±1.0)	38.2(±2.3)

TABLE 12-7. VOLKSWAGEN PARTICULATE EMISSIONS AND SOLUBLE ORGANIC FRACTIONS RECORDED IN EPA TESTS<sup>(12-1)</sup>

Emissions	Fuel	Driving Cycle				Special Cycle	45 SS
		FTP	HFET	CUE	NYCC		
Total Particles, g/mi	Amoco	0.45(±.04)	0.45(±.03)	0.37(±.03)	0.44(±.04)	0.41(±.01)	0.26(±.01)
	Ref.	0.36(±.02)	0.37(±.01)	0.30(±.03)	0.43(±.04)	0.36(±.02)	0.29(±.02)
	RTP-100	0.40(±.05)	0.41(±.04)	0.34(±.02)	0.44(±.02)	0.38(±.03)	0.26(±.03)
	Shale	0.40(±.07)	0.39(±.0)	0.32(±.02)	0.45(±.03)	0.38(±.03)	0.28(±0.0)
DCM Soluble Organic, % parti- culate	Amoco	17(±1)	18(±1)	17(±1)	17(±1)	17(±1)	21(±1)
	Ref.	20(±1)	21(±1)	19(±1)	18(±1)	18(±1)	20(±3)
	RTP-100	19(±2)	19(±1)	17(±1)	18(±1)	17(±1)	21(±2)
	Shale	19(±1)	20(±0)	19(±1)	19(±1)	19(±1)	20(±0)

TABLE 12-8. OLDSMOBILE PARTICULATE EMISSIONS AND SOLUBLE ORGANIC FRACTIONS RECORDED IN EPA TESTS<sup>(12-1)</sup>

Emissions	Fuel	Driving Cycle				Special Cycle	45 SS
		FTP	HFET	CUE	NYCC		
Total Particles, g/mi	Amoco	0.57(±.08)	0.39(±.02)	0.47(±.04)	1.00(±.07)	0.76(±.07)	0.18(±.03)
	Ref.	0.57(±.05)	0.38(±.03)	0.44(±.04)	0.93(±.08)	0.80(±.10)	0.18(±.01)
	RTP-100	0.60(±.05)	0.40(±.02)	0.48(±.08)	0.90(±.08)	0.83(±.14)	0.17(±.01)
	Shale	0.50(±.08)	0.22(±.01)	0.37(±.06)	0.76(±.10)	0.59(±.10)	0.14(±.02)
DCM Soluble Organics % parti- culate	Amoco	16(±2)	17(±1)	14(±1)	16(±1)	11(±1)	25(±1)
	Ref.	14(±1)	18(±3)	14(±1)	15(±2)	11(±2)	26(±2)
	RTP-100	13(±1)	17(±3)	11(±1)	15(±2)	9(±1)	24(±1)
	Shale	18(±2)	21(±3)	17(±3)	18(±3)	12(±2)	30(±4)

TABLE 12-9. RESULTS OF BIOASSAY FOR MUTAGENIC ACTIVITY USING PARTICULATES FROM FEDERAL TEST PROCEDURE CONDUCTED BY EPA<sup>(12-1)</sup>

<u>Fuel</u>	<u>Metabolic Activation</u>	<u>Thousands of Revertants/Mile</u>	
		<u>Volkswagen</u>	<u>Oldsmobile</u>
Amoco	yes	368	136
	no	252	331
Referee	yes	360	212
	no	346	384
Shale DFM	yes	555	90
	no	821	288
Union 76	yes	316	265
	no	344	187

TABLE 12-10. PROPERTIES OF FUELS TESTED IN TURBOCHARGED VOLKSWAGEN RABBIT BY DOT/TSC<sup>(12-2)</sup>

	<u>EPA-ESRL #2 DIESEL</u>	<u>DFM-2 SHALE-OIL BASE</u>
Hydrogen Carbon Ratio	1.79	1.86
Specific Gravity	0.8488	0.8353
BTU/lb	19,541	19,568
BTU/gallon	138,116	136,095
Hydrogen, %	13.03	13.44
Carbon, %	86.75	85.83
Sulfur, %	0.25	0.20
Cetane Index	48.8	54.5
Distillation Range °F		
IBP	387	414
10%	430	455
50%	509	510
90%	599	562
End Point	652	594
Recovery, %	98.5	99.0

\*Analyses performed by Skinner and Sherman, Inc.,  
New England Laboratories, Waltham, Massachusetts.

TABLE 12-11. PROPERTIES OF FUELS TESTED IN 1980  
VOLKSWAGEN RABBIT BY SWRI(12-4)

Substance	Base DF-2	Shale Diesel Marine	Paraho JP-5	Coal Case 5A	35% SRC-II	Broadcut Mid-Continent	25% SRC-II	25% EDS	25% EDS Naphtha
Fuel Code (EN-)	329-F	453-F	473-F	474-F	475-F	476-F	478-F	482-F	485-F
Cetane No. (D613)	50	49	45	42	31	35	38	44	45
Cetane Index (D976)	52	56	46	41	29	52	38	42	47
Gravity, °API @ 60°F	37.5	37.9	43.6	31.1	28.2	44.1	31.7	33.8	38.3
Density, g/ml @ 60°F	0.837	0.835	0.808	0.870	0.845	0.806	0.867	0.856	0.833
Carbon, wt. %	85.8	86.3	85.9	86.5	86.2	86.1	86.4	86.5	86.3
Hydrogen, wt. %	13.0	13.4	13.7	12.4	11.8	13.2	12.3	12.7	13.3
Nitrogen, ppm (oxid. pyrolysis)	48	5	<1	1600	3400	1000	2000	267	142
Sulfur (lamp) %	0.24	<0.005	0.005	0.100	0.31	0.17	0.23	0.16	0.28
Calculated H/C, numeric	1.81	1.85	1.90	1.71	1.52	1.83	1.70	1.75	1.84
Carbon No. range (G.C.)	8-24	9-20	10-15	9-24	8-20	3-24	8-20	8-20	7-20
Aromatics, vol. %	21.3	28.5	22.0	34.9	47.0	16.2	39.9	36.4	25.5
Olefins, vol. % (D1319)	1.7	2.1	2.0	1.4	0.6	0.0	1.2	0.0	0.5
Paraffins, vol. %	77.0	69.4	76.0	63.7	52.4	83.8	58.9	63.6	74.0
Viscosity, cSt @ 100°F (D445)	2.36	2.61	1.38	3.08	2.53	1.53	2.45	2.37	1.76
Gum, mg/100 ml (D481)	14.3	0.3	1.4	38.8	89.7 <sup>b</sup>	23.8	30.1	60.0	13.1
Total solids, mg/l	7.4	0.3			13.1		7.2	3.1	1.2
Metals in fuel, x-ray	0 <sup>a</sup>	0 <sup>a</sup>	0	0	0	0	9ppm Fe	0	0
Boiling Range, °C (IBP-EP, D86)	191-340	207-317	179-248	192-366	171-328	21-354	178-327	179-353	103-334
10% point	219	236	199	234	207	53	209	207	157
20% point	231	246	192	244	215	121	220	218	182
30% point	242	252	196	253	225	151	231	227	203
40% point	251	259	198	259	234	178	240	239	223
50% point	260	266	202	267	243	216	250	251	238
60% point	269	272	206	276	252	239	259	263	254
70% point	278	278	211	277	263	255	270	276	267
80% point	290	286	218	292	274	270	281	293	281
90% point	307	295	228	330	292	303	303	316	302
95% point	323	302	237	353	309	327	319	336	319
Residue, wt. % (D86)	1.3	1.0	1.5	1.5	1.0	1.0	1.0	1.5	1.5
Boiling Range, °C (IBP-EP, D2887)	104-387	118-341	157-286	140-416	103-346	24-399	129-508	128-419	72-455
10% point	197	216	175	217	158	68	193	192	139
20% point	220	237	187	238	178	123	214	210	174
30% point	239	254	195	254	196	155	232	228	197
40% point	256	265	201	264	207	196	248	243	225
50% point	268	274	210	271	219	233	259	257	249
60% point	280	285	216	284	229	251	271	273	264
70% point	292	297	224	299	240	262	285	289	279
80% point	307	307	234	315	255	280	302	305	298
90% point	330	319	244	344	278	314	321	332	314
95% point	347	325	254	367	295	342	345	356	336
Residue, wt. % (D2887)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>Composition, Volume %</b>									
<b>Kerosene</b>									
Petroleum	0.0	0.0	0.0	17.3	0.0	22.0	0.0	0.0	0.0
Shale JP-5	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
<b>Diesel</b>									
Petroleum	100.0	0.0	0.0	66.7	65.0	23.0	75.0	75.0	75.0
Shale DPM	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal	0.0	0.0	0.0	16.0	35.0	6.2	25.0	25.0	25.0
Light Cycle Oil (petroleum)	0.0	0.0	0.0	0.0	0.0	5.2	0.0	0.0	0.0
LSR Naptha (petroleum)	0.0	0.0	0.0	0.0	0.0	7.4	0.0	0.0	0.0
<b>MSR</b>									
Petroleum	0.0	0.0	0.0	0.0	0.0	4.8	0.0	0.0	0.0
Shale	0.0	0.0	0.0	0.0	0.0	20.9	0.0	0.0	0.0
N-Butane	0.0	0.0	0.0	0.0	0.0	10.5	0.0	0.0	0.0

<sup>a</sup> <10 ppm of Cr, Fe, Ni, Cu, Zn, and Mg; <70 ppm Pb; <100 ppm Al and Si  
<sup>b</sup> Sample not dry after 1 hr. in steam lit block



TABLE 12-12. RESULTS OF BIOASSAY FOR MUTAGENIC ACTIVITY USING PARTICULATES FROM FEDERAL TEST PROCEDURE CONDUCTED BY SWRI<sup>(12-3)</sup>

Fuel Code	Description	RLI-16 Activation	Model Predicted Mean Slope, 10 <sup>3</sup> revertants/km				
			TA-1535	TA-1537	TA-1538	TA-98	TA-100
EM-329-F	base DF-2	No	18	70	135	219	624
		Yes	4	51	128	113	263
EM-453-F	shale diesel marine (DFM)	No	24	204	313	568	1444
		Yes	5	227	521	298	687
EM-473-F	Paraho JP-5	No	0	177	250	202	525
		Yes	7	70	378	147	447
EM-474-F	Coal Case 5A	No	0	296	423	673	1214
		Yes	5	204	444	265	1055
EM-476-F	Broadcut	No	0	316	552	771	2564
		Yes	12	242	610	288	817
EM-478-F	25% SRC-II	No	34	365	580	603	3553
		Yes	4	406	696	307	794
EM-482-F	25% EDS	No	5	620	566	1206	978
		Yes	10	407	541	437	809
EM-485-F	25% EDS naphtha	No	0	486	681	729	641
		Yes	4	449	597	331	316

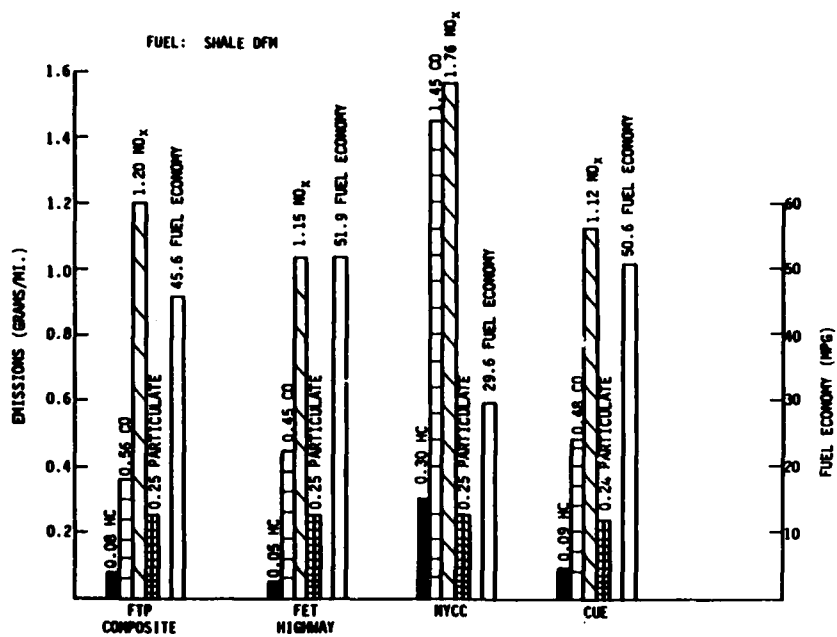


FIGURE 12-1. EMISSIONS AND FUEL ECONOMY OF TURBOCHARGED VOLKSWAGEN RABBIT OVER VARIOUS DRIVING CYCLES RECORDED BY DOT/TSC<sup>(12-2)</sup>

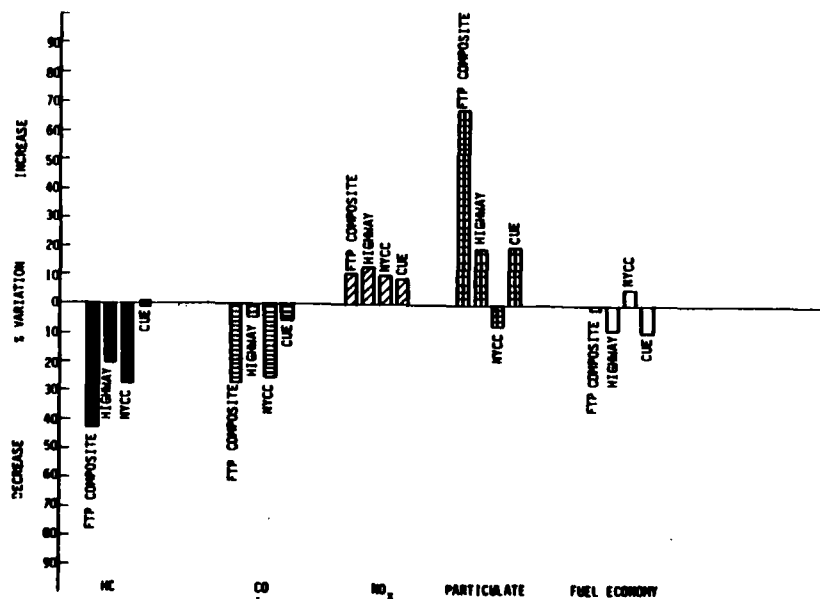


FIGURE 12-2. PERCENT VARIATION IN EMISSIONS AND FUEL ECONOMY BETWEEN PETROLEUM DF-2 AND SHALE DFM IN DOT/TSC TESTS<sup>(12-2)</sup>

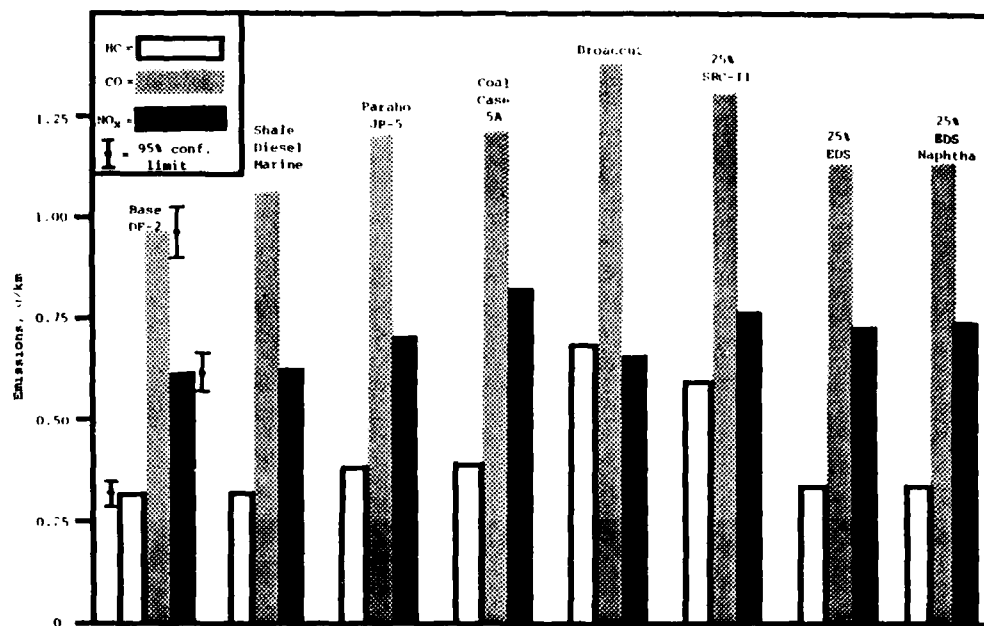


FIGURE 12-3. REGULATED GASEOUS EMISSIONS DURING FEDERAL TEST PROCEDURE RECORDED BY SWRI<sup>(12-3)</sup>

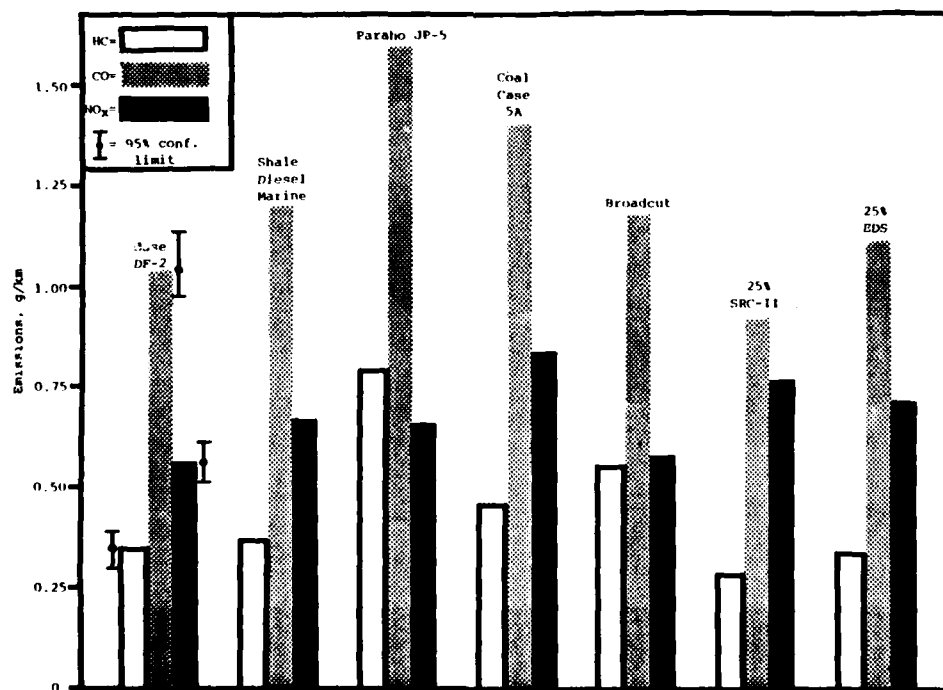


FIGURE 12-4. REGULATED GASEOUS EMISSIONS DURING HIGHWAY FUEL ECONOMY TEST RECORDED BY SWRI<sup>(12-3)</sup>

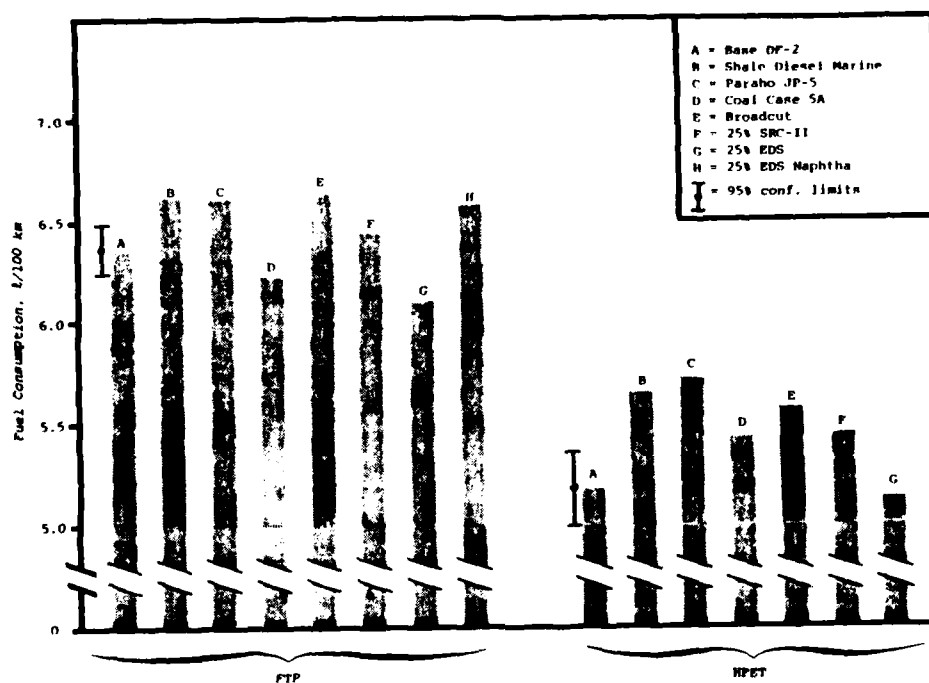


FIGURE 12-5. FUEL CONSUMPTION DURING FEDERAL TEST PROCEDURE AND HIGHWAY FUEL ECONOMY TEST RECORDED BY SWRI<sup>(12-3)</sup>

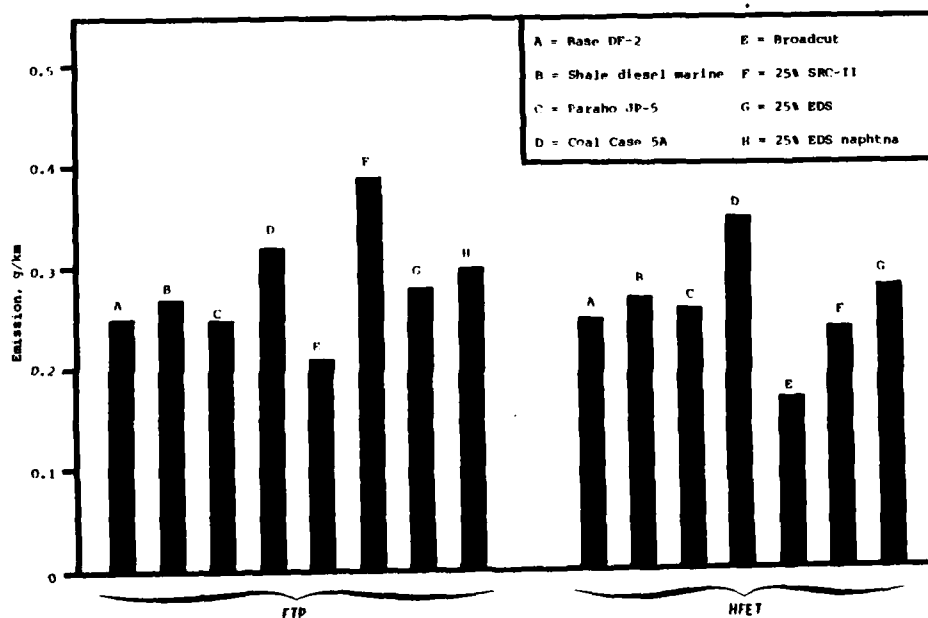


FIGURE 12-6. PARTICULATE EMISSIONS DURING FEDERAL TEST PROCEDURE AND HIGHWAY FUEL ECONOMY TEST RECORDED BY SWRI<sup>(12-3)</sup>

### 13. MISCELLANEOUS TESTS

#### Introduction

This section summarizes the results of five investigations of engine performance on various shale derivatives. The fuels tested include shale DFM, shale JP-5, shale gasoline and a heavy shale distillate. The fuels were evaluated in a diverse assortment of engines, including automotive diesels, single-cylinder diesel and gasoline engines, a gas turbine combustor and an automotive Stirling engine.

Table 13-1 describes the engines tested, the evaluating organizations and the fuels burned in each device. A petroleum fuel was also burned in each test, as well as various other alternative fuels in many of the investigations.

The General Motors fleet evaluation of shale DFM was the most ambitious of the five tests. Two Oldsmobiles were each driven 30,000 miles on shale DFM during a two-year period. A third vehicle was driven on conventional diesel fuel as a control. The fuel consumption and emissions of the three vehicles were recorded at regular intervals and the engines were inspected at the completion of testing for wear and deposits. Shale DFM and shale JP-5 were also burned by General Motors in a single-cylinder diesel engine to confirm its operability.

Caterpillar Tractor Company performed an evaluation of shale DFM in a single-cylinder diesel engine for the David Taylor Naval Ship Research and Development Center (DTNSRDC). The engine was operated at partial and full load at two rotational speeds. Fuel consumption and emissions of particulates,  $\text{NO}_x$ , and hydrocarbons were measured.

Mechanical Technology Incorporated (MTI) burned shale DFM and four other fuels in an automotive Stirling engine. The project was sponsored by NASA/Lewis Research Center. The objective was to assess the fuel sensitivity of the engine in terms of emissions and fuel consumption.

A heavy shale distillate was burned in a gas turbine combustor by Westinghouse Electric Corporation under the sponsorship of the Electric Power Research Institute. The primary objective was to evaluate  $\text{NO}_x$  emissions from high-nitrogen fuels emulsified with water. Two H-coal distillates and a No. 2 oil doped with quinoline were also tested.

Ford Motor Company burned weathered gasoline derived from shale oil in a single-cylinder PROCO (Programmed Combustion) engine. This is a developmental stratified-charge spark-ignition engine. Indolene Clear was burned for comparison. The shale-derived gasoline was supplied to Ford directly by Sohio. The objective was to measure fuel consumption, thermal efficiency and emissions of  $\text{CO}$ ,  $\text{NO}_x$  and hydrocarbons at a variety of engine loads and speeds.

The following subsections describe the procedures, results and conclusions from each of these investigations.

#### General Motors Fleet Evaluation of Shale DFM (13-1,2)

The object of this investigation was to evaluate the long-term use of shale DFM in production automotive engines under realistic driving conditions. Because testing took place in Michigan over a period of two years, the vehicles were exposed to a broad range of climatic and driving conditions. The results therefore complement the observations recorded under more carefully controlled but less realistic operating conditions maintained in other diesel engine studies summarized herein (e.g., the MERADCOM and EPA studies reported in Sections 10 and 12).

#### Procedure

A preliminary test was conducted in which shale DFM and shale JP-5 were burned in a single-cylinder diesel engine to confirm their operability in a diesel engine. The engine performed well on both fuels. The favorable results cleared the way for a fleet evaluation in which two Oldsmobile 88 Delta Royales with 350 CID Oldsmobile diesel engines were fueled with the shale DFM. An identical car was operated on a conventional DF-2 fuel. Each vehicle was driven 30,000 miles between December 1980 and November 1982. Emissions and fuel economy were measured at 5000 mile intervals. The engines were disassembled and inspected after 30,000 miles for fuel-related adverse effects.

#### Results

Fuel economy was unaffected by burning shale DFM. Hydrocarbon and CO measurements were slightly higher and particulate and NO<sub>x</sub> emissions slightly lower for shale DFM than for the DF-2. The differences were not expected to be statistically significant.

Low temperature flow properties of the shale DFM were troublesome. Starting difficulties were experienced at ambient temperatures of -5 to -10 F, the approximate cloud point for the shale DFM. A high wax concentration at low temperatures was apparently the cause. The fuel responded poorly to flow-improver additives. Blending with petroleum-derived fuels may eliminate the problem.

No fuel-related wear or deposit problems were found on disassembly and inspection. Shale DFM performed comparably to the DF-2 fuel in all aspects of engine durability.

### Conclusions

Shale DFM and a petroleum DF-2 fuel were tested in an automotive fleet during the period from December 1980 to November 1982. Each car was driven 30,000 miles. Differences in fuel economy and emissions attributable to fuel type were statistically insignificant. Starting difficulties were experienced with shale DFM at temperatures of -5 to -10 F due to high wax concentrations. Blending with petroleum-derived fuels may eliminate the problem. An inspection after 30,000 miles revealed no engine wear or deposition problems for either fuel. Based on these results, shale DFM appears to be an acceptable substitute for petroleum-derived diesel fuel in all aspects of automotive performance except cold-weather starting.

### Caterpillar Single-Cylinder Engine Evaluation of Shale DFM(13-3,4)

The objective of this test was to compare the performance and emissions characteristics of shale DFM and petroleum-based 1E262 diesel fuel (Caterpillar's referee DF-2 fuel) in a Caterpillar Model 3301 PC-T single-cylinder test engine. The test was carried out for DTNSRDC, located at Annapolis, Maryland.

### Procedure

The properties of the shale DFM and petroleum 1E262 diesel fuel were evaluated. The two fuels were then burned in a single-cylinder engine. Brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC) and brake-specific energy consumption (BSEC) were measured under partial and full load at 1400 and 2200 RPM. Emissions (smoke, HC and NO<sub>x</sub>) were also measured under the aforementioned conditions. In addition, HC and NO<sub>x</sub> were measured at speeds of 1400 and 2200 RPM with no load on the engine.

### Results

Table 13-2 shows Caterpillar's fuel analyses. The two fuels were, in general, quite similar. The shale DFM exhibited a lower density, higher heating value and higher cetane number and was accordingly marginally superior to the standard 1E262 diesel fuel.

Table 13-3 summarizes engine performance and emissions using the two fuels at full load and idle. The BMEP exhibited by the engine was virtually identical for the two fuels, implying that the use of shale DFM causes no reduction in engine power output. Energy consumption was higher when burning shale DFM by roughly 4 and 2 percent at 2200 and 1400 RPM, respectively. Partial load performance was virtually identical for the two fuels at both 1400 and 2200 RPM. In addition, no

significant differences in emissions levels were observed under any conditions tested.

### Conclusions

Shale DFM was tested in a single-cylinder engine and was found to be a fully acceptable fuel. The only undesirable feature exhibited by the shale DFM was a 2 to 4 percent increase in BSEC as compared to the petroleum fuel. However, this detriment was moderated by the fact that the volumetric heating value of the shale DFM was 1.6 percent higher than that of the petroleum fuel.

### MTI Alternative Fuels Evaluation in an Automotive Stirling Engine(13-5,6)

The objective of this study was to assess fuel consumption and emissions from an automotive Stirling engine while burning five different fuels.

### Procedure

Five fuels were burned in a 53-HP United Stirling P-40 engine: unleaded gasoline, shale DFM, gasohol, a commercial DF-2 diesel fuel, and NASA's Experimental Referee Broad-Specification turbine fuel (ERBS). A fuel properties analysis was prepared for each. Engine speed and load were varied according to a 16-point test matrix for each fuel. Fuel consumption and emissions ( $\text{NO}_x$ , NO, HC and CO) were measured for each fuel with and without exhaust gas recirculation (EGR). Cold and hot starting difficulties were assessed.

### Results

The performance of the Stirling engine in terms of both fuel consumption and emissions was similar for all fuels tested. Shale DFM proved slightly superior to the other fuels in terms of net power output and efficiency. Analysis of the emissions data revealed no important trends with fuel type for any of the species monitored. EGR was beneficial in reducing emissions of all species, particularly  $\text{NO}_x$ .  $\text{NO}_x$  emissions without EGR were typically 3 to 4 times as great as with EGR regardless of fuel types.

Hot starting immediately after shutdown was possible with all fuels. When warm starting with diesel fuels was attempted, with heater tubes at 480 to 570 F, dense gray smoke was produced. Cold starting, with heater tubes at 48 to 68 F, was not possible with diesel fuels. The engine was fired with gasoline and switched over to diesel fuel when hot in order to run tests with DF-2 or shale DFM.



## Conclusions

Shale DFM and four other hydrocarbon fuels were evaluated in terms of fuel consumption and emissions in a Stirling engine. The performance of the engine was similar for all fuels tested. Based on these results, shale DFM appears to be equivalent to DF-2 fuel for this automotive Stirling engine. To fire DF-2 or shale DFM it was necessary to first bring the heat exchanger up to operating temperature by firing gasoline.

## Westinghouse Gas Turbine Combustor NO<sub>x</sub> Emission Tests(13-7)

Four high-nitrogen fuels were emulsified with water at various water/fuel ratios and burned in a half-scale gas turbine combustor test rig. Number 2 distillate fuel was also burned to provide a baseline for comparison. The objective was to evaluate the influence of water/fuel ratio on total NO<sub>x</sub> production and on the conversion of fuel-bound nitrogen to NO<sub>x</sub>. Smoke number and HC and CO emissions were also monitored. The shale fuel used was a hydrogenated heavy distillate containing 0.33 percent nitrogen.

## Procedure

All tests were run at simulated base-load conditions with 1.5 lb/sec air at 103 psia and 600 F. The water and fuel were fired as an emulsion, with water/fuel mass ratios ranging from zero to 1.2. The results of a previous test in which water had been sprayed separately into the flame provided a measure of the effectiveness of the emulsion technique.

Each test with an experimental fuel was preceded by a test in which a No. 2 distillate was fired, both dry and with water injection. The nitrogen content of the distillate fuel (0.008 percent) was essentially negligible compared to the contents of the experimental fuels. The heavy shale distillate, for instance, had a nitrogen content of 0.33 percent. The shale distillate was fired at a temperature of 395 K (248 F) so that its viscosity was identical to that of the No. 2 petroleum distillate.

Samples were extracted from the combustor exhaust with a gas analysis rake. NO<sub>x</sub> measurements were made with two devices, a chemiluminescent detector and a wet-cell analyzer. Hydrocarbon, CO, CO<sub>2</sub> and smoke measurements were also made.

## Results

Figure 13-1 presents the total NO<sub>x</sub> nitrogen oxide emissions as a function of water/fuel mass ratio for the heavy shale distillate.

Curve I in the figure represents the results achieved with water injected as an emulsion, while Curve II corresponds to the previous tests in which water was sprayed separately into the flame. The base line curve indicates the results achieved with the No.2 petroleum distillate in which water was injected as an emulsion.

The results of Figure 13-1 show clearly that water injection is largely ineffective at reducing  $\text{NO}_x$  emissions when burning high-nitrogen fuels. The shale distillate  $\text{NO}_x$  emissions are reduced slightly as water/fuel mass ratio is increased from zero to 0.4. However, no further decrease is observed at higher water/fuel mass ratios. In contrast, the  $\text{NO}_x$  emissions produced by the No. 2 petroleum distillate decrease monotonically with increasing water/fuel mass ratio over the full range tested. The other experimental fuels, which had fuel nitrogen contents ranging from 0.16 to 0.33 percent, exhibited the same trends with water/fuel ratio as the shale distillate. In all cases where direct comparisons were made, water introduced as an emulsion was more effective at reducing  $\text{NO}_x$  emissions than water introduced as a spray.

Figure 13-2 shows the effect of water injection on the conversion of fuel-bound nitrogen (FBN) to  $\text{NO}_x$ . The  $\text{NO}_x$  produced from FBN was calculated by subtracting the thermal  $\text{NO}_x$  (as determined via the base-line petroleum distillate fuel experiments) from the total  $\text{NO}_x$  measured at each water/fuel ratio. The solid curve of Figure 13-2 represents the results achieved with water introduced as an emulsion, while the water spray results are signified by the broken line. In both cases, FBN conversion to  $\text{NO}_x$  increased with increased water/fuel ratio. This trend was also observed with the other experimental fuels. Water introduced as an emulsion was more effective at limiting the conversion of FBN to  $\text{NO}_x$  than water sprayed into the flame.

The effect of water/fuel ratio on smoke, CO and HC emissions was also observed in these experiments. Smoke number decreased with increasing water/fuel ratio. The authors cite two possible reasons for this trend: (1) the hydroxyl radical, which is effective in oxidizing soot precursors, becomes more plentiful with increased water/fuel ratio and (2) better atomization and mixing are achieved with increased water/fuel ratio due to droplet explosions.

Unfortunately, CO and HC emissions increase with water/fuel ratio, presumably due to quenching in certain regions of the flame. The increases are significant even at low water/fuel ratios and become precipitous at high ratios where the flame becomes rather unstable.

### Conclusions

The effect of water injection on  $\text{NO}_x$  emissions from a gas turbine combustor burning high-nitrogen fuels was investigated. Water was introduced as an emulsion with the fuel in the present tests. The

results were compared with those from previous experiments in which water was sprayed separately into the flame. The effect of water injection on smoke, CO and HC emissions was also investigated.

Water injection was found to be largely ineffective at limiting NO<sub>x</sub> emissions from high-nitrogen fuels. For a heavy shale distillate containing 0.33 percent nitrogen content, water injection reduced NO<sub>x</sub> emissions by only about 15 percent. In contrast, water injection reduced the NO<sub>x</sub> emissions from a No. 2 petroleum distillate of 0.008 percent nitrogen content by roughly 80 percent. In all cases, water introduced as an emulsion was more effective at controlling emissions than water sprayed into the flame separately.

Smoke emissions decreased significantly with water/fuel ratio. Hydrocarbon and CO emissions increased with water/fuel ratio, presumably due to quenching. The conversion of fuel-bound nitrogen to NO<sub>x</sub> also increased with water/fuel ratio.

Based on these results, water injection does not appear to be a feasible means of reducing NO<sub>x</sub> emissions from gas turbine combustors burning high-nitrogen fuels.

#### Ford Motor Company Evaluation of Weathered Shale Gasoline(13-8)

Ford Motor Company tested a shale-derived gasoline in a single-cylinder PROCO (Programmed Combustion stratified-charge, spark-ignition) engine at their research center in Dearborn, Michigan. Indolene Clear gasoline was also burned as a comparison fuel. The objective was to evaluate fuel consumption, thermal efficiency and emissions with the shale fuel at a variety of engine speeds and loads. The shale-derived weathered gasoline was an unfinished naphtha cut having a low octane rating, and would not be a suitable fuel for a conventional automotive gasoline engine. However, the PROCO engine is relatively insensitive to fuel octane number.

#### Procedure

Fuel property evaluations were completed for the shale gasoline and Indolene Clear. The shale gasoline had a lower octane rating and a higher initial boiling point.

A detailed test matrix was employed in evaluating the two fuels. Engine load and speed, equivalence ratio and spark and injection timing were all varied. The engine was a dual-spark ignition device with a displacement of 50 cubic inches and a compression ratio of 11.7:1. Because of the low octane rating of the shale gasoline, engine operation was limited by knock and harshness to the extent that a portion of the test matrix could not be completed. Fuel consumption,

thermal efficiency and emissions of HC, NO<sub>x</sub>, and CO were measured at each condition tested.

### Results

Significant differences in all the performance indicators were observed over at least portions of the test matrix. NO<sub>x</sub> emissions in particular were subject to substantial variations, but no clear trend emerged to indicate whether one fuel or the other was more prone to NO<sub>x</sub> production. The thermal efficiencies exhibited by the two fuels were the most consistent of the performance indicators and revealed no significant difference between the two.

Hydrocarbon and CO emissions were generally higher with the shale gasoline than with the Indolene Clear fuel, particularly at low engine speeds and load. Under these conditions, mixing of fuel and air in the cylinder is relatively poor; the overall higher distillation curve of the shale gasoline probably results in incomplete or delayed evaporation of the fuel with a corresponding increase in HC and CO emissions.

### Conclusions

A weathered shale-derived gasoline and Indolene Clear fuel were burned in a single-cylinder PROCO engine. Engine speed and load, equivalence ratio and spark and injection timing were routinely varied. Thermal efficiency, fuel consumption and emissions of HC, CO and NO<sub>x</sub> were measured.

The low octane rating of the shale gasoline caused engine knock and harshness that restricted the range of conditions that could be tested. Engine thermal efficiency and NO<sub>x</sub> emissions were not consistently different for the two fuels across major portions of the test matrix. Higher HC and CO emissions exhibited by the shale gasoline, particularly at low engine speed and load, were attributed to the shale fuel's higher distillation curve.

The shale gasoline as tested is probably not suitable for use in commercial gasoline engines as a replacement for petroleum fuels. However, refining changes to boost its octane rating and lower its boiling range would probably make shale-derived gasoline acceptable for such service.

References

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- 13-5. Daly, J. W., "Combined Alternate Fuels and General Development Test Results of ASE P-40-7", MTI Report No. 82ASE264ER38, Mechanical Technology Incorporated, Latham, New York, August, 1982.
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- 13-7. Singh, P. P., Mulik, P. R. and Cohn, A., "Effect of Using Emulsions of High Nitrogen Containing Fuels and Water in a Gas Turbine Combustor on NO<sub>x</sub> and Other Emissions", Journal of Engineering for Power 105, July, 1983, pp. 430-437.
- 13-8. Freeman, L. E., Roby, R. J., and Chui, G. K., "Single Cylinder Engine Test Results Obtained from Sohio 'Weathered' Gasoline Feedstock Shale Liquid", undated Ford Motor Company internal report, Dearborn, Michigan.

TABLE 13-1. SUMMARY OF ENGINES AND FUELS TESTED

<u>Evaluating Organization</u>	<u>Engine or Vehicle Description</u>	<u>Fuels Evaluated</u>	<u>References</u>
General Motors	Oldsmobile 88 Delta Royale, single-cylinder test engine	Shale DFM, Shale JP-5	13-1,2
Caterpillar Tractor Co.	Model 3301 PC-T single- cylinder test engine	Shale DFM	13-3,4
Mechanical Tech- nology, Inc.	53-horsepower automotive Stirling engine	Shale DFM	13-5,6
Westinghouse Electric Corp.	14-cm diameter gas turbine can-type combustor	Shale heavy distillate	13-7
Ford Motor Company	Single-cylinder PROCO gasoline engine	Weathered shale- derived gasoline	13-8

TABLE 13-2. PROPERTIES OF FUELS EVALUATED IN  
CATERPILLAR SINGLE-CYLINDER DIESEL ENGINE<sup>(13-4)</sup>

	<u>DF-2</u>	<u>Shale DFM</u>
CAT No.	1E262	4189
Gravity		
API	35	38.2
Specific Gravity	.85	.8338
lb/gal	7.0923	6.9585
Cetane Index	42-43	50-53
Low Heat Value		
BTU/lb	18330	18980
BTU/gal	130,000	132,060
BTU increase by wt.		3.5%
BTU increase by vol.		1.6%
Viscosity @ 100°F (SUS)	33-40	34.8
Pour Point	0°F	-5°F
Cloud Point	10°F	-2°F
Distillation		
1BP (°F)	430	372
90% (°F)	625	560
EP (°F)	675	580
Sulphur %	.35-.45	Nil
Ash %	.02	< .001

TABLE 13-3. CATERPILLAR SINGLE-CYLINDER ENGINE TEST  
RESULTS AT FULL LOAD AND IDLE<sup>(13-4)</sup>

	Petroleum DF-2	Shale DFM
I. 2200 rpm - max load (fixed rack @ .440)		
BMEP (psi)	125	126
BSFC (lb/bhp-hr)	.447	.448
BSEC (btu/bhp-hr)	8194	8503
Smoke	.03	.03
HC (gr/bhp-hr)	.09	.03
NO <sub>x</sub> (gr/bhp-hr)	1.17	1.25
II. 2200 rpm - idle		
HC (gr/bhp-hr)	.09	.15
NO <sub>x</sub> (gr/bhp-hr)	.22	.16
III. 1400 rpm - max load (fixed rack @ .440)		
BMEP (psi)	142	142
BSFC (lb/bhp-hr)	.411	.406
BSEC (btu/bhp-hr)	7534	7706
Smoke	.08	.11
HC (gr/bhp-hr)	.12	.12
NO <sub>x</sub> (gr/bhp-hr)	.57	.51
IV. 1400 rpm - idle		
HC (gr/bhp-hr)	.05	.06
NO <sub>x</sub> (gr/bhp-hr)	.12	.11

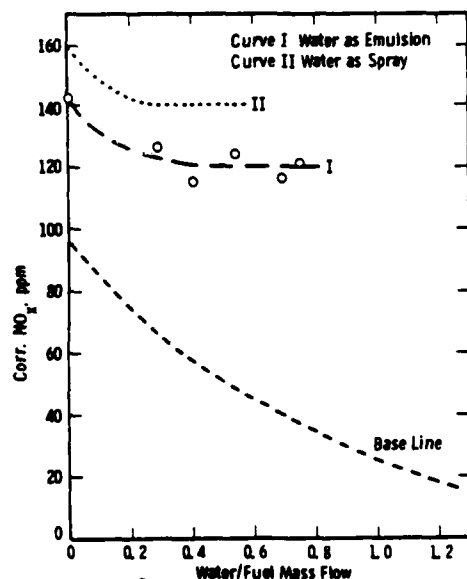


FIGURE 13-1. EFFECT OF WATER  
INJECTION ON NO<sub>x</sub> EMISSIONS FOR  
HEAVY SHALE DISTILLATE<sup>(13-7)</sup>  
(Westinghouse Combustor Rig Tests)

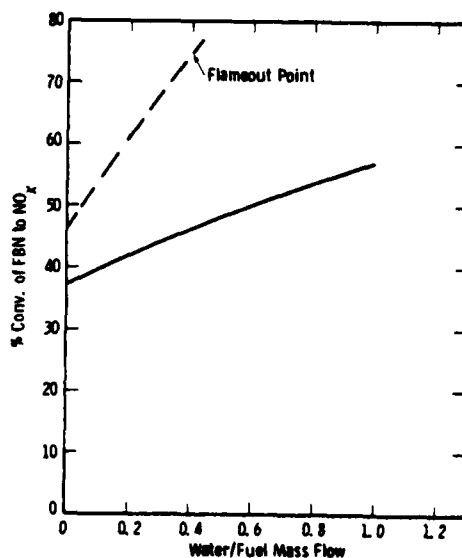


FIGURE 13-2. EFFECT OF WATER INJECTION  
ON CONVERSION OF FUEL-BOUND NITROGEN  
TO NO<sub>x</sub> FOR HEAVY SHALE DISTILLATE<sup>(13-7)</sup>  
(Westinghouse Combustor Rig Tests)

## 14. SHALE RESIDUAL FUEL TESTS

Introduction

Shale residual fuel has been evaluated for use in heavy-duty gas turbines and diesel engines by tests of a Brown Boveri 35-MW turbine having a single, large combustion chamber designed for use with residual fuel(14-1), and by tests of an APE Allen medium-speed diesel engine used widely with residual fuel(14-2). In both tests, the shale residual fuel proved to be a suitable fuel, performing more like No. 2 diesel fuel than like petroleum residual fuel. The evaluations were carried out for DOE.

Tests of the Brown-Boveri Type 9 Gas TurbineObjective

The Brown-Boveri (BBC) Type 9 gas turbine test was carried out by Stone and Webster Engineering Corporation, Boston, Massachusetts, as part of a study of the applicability of alternate fuels to utility gas turbines. The objective of the test was to evaluate the use of three alternate fuels in gas turbines designed for firing residual oil. The three fuels were pyrolysis oil, shale residual oil, and a coal-derived middle distillate.

Procedure

The procedure consisted of firing each of the three alternate fuels plus a conventional No. 2 diesel fuel in a BBC Ltd. Type 9, 35 MW, gas turbine. Testing took place at BBC's facilities near Basel, Switzerland. Each fuel was burned for a period of 10 to 15 hours under conditions ranging from idle to full load. Cold and hot starts were performed to evaluate the transient behavior of the fuels. The turbine was disassembled after each fuel was tested to inspect for erosion and corrosion. Combustor liner temperatures and pollutant emissions were measured for all fuels tested. Combustor liner temperature is of concern because of the low hydrogen content of alternative fuels and the correspondingly high flame radiation levels. Pollutant species that were monitored include particulates, NO<sub>x</sub>, CO, hydrocarbons (HC), and polynuclear aromatics (PNA). The latter were measured due to their prevalence in heavily aromatic fuels and their potential carcinogenicity.

Results

A detailed analysis of the residual shale oil is presented in Tables 14-1 and 14-2. Due to its high viscosity, the residual shale oil was preheated to 50 C to 70 C (122 F to 158 F) before firing. The



aromatic content of the residual shale oil, at 33.6 percent, was substantially less than that of the Exxon Donor Solvent (EDS) coal liquid (71 percent) and the pyrolysis fuel oil (52.8 percent).

Combustor liner temperatures were correlated against fuel hydrogen content and showed the expected result that liner temperatures increase with decreasing fuel hydrogen content. Liner temperatures when firing EDS distillate fuel containing 10.0 percent hydrogen, and pyrolysis fuel containing 7.5 percent hydrogen, were 2 percent and 9 percent above those for the baseline No. 2 diesel fuel containing 13.6 percent hydrogen. Liner temperatures when firing shale residual fuel containing 13.0 percent hydrogen, however, were 2 percent below those for the baseline fuel. All liner temperatures were within design limits.

Pollutant emissions while burning residual shale fuel were comparable with those for No. 2 diesel fuel for nearly all species under all conditions. The only exception observed was in PNA emissions at idle speed, where the value of 10 micrograms per cubic meter was about twice that for the baseline fuel. However, this level was considered acceptable.

### Conclusions

Residual shale oil and two other alternative liquid fuels were burned in a 35 MW gas turbine designed for crude and residual oil firing. Combustor liner temperatures and emission levels while burning residual shale oil were comparable to those observed when burning No. 2 diesel fuel. The results suggest that residual shale oil is an acceptable substitute for petroleum-derived fuels in heavy-duty gas turbines as used for electric utility peaking service.

### Use of Shale Residual Fuel in a Medium-Speed Diesel Engine

#### Introduction

As part of a DOE study to explore the potential for utilization of alternate fuels in medium-speed engines, a residual shale oil from the Paraho/Sohio 100,000 bbl shale program was fired to an APE Allen S300 diesel engine. Residual fuels are used widely for ship propulsion using medium-speed diesel engines, and there appears to be some potential for locomotive application. The study was conducted by Acurex Corp., with diesel engine tests carried out by Ricardo Engineering(14-2).

The APE Allen S300 diesel engine used for these tests is a European six-cylinder engine with a 9.5-inch bore, 12-inch stroke, pressure ratio of 12, and power rating of 774 hp at 750 rpm. It utilizes a 4-stroke cycle with turbocharging and aftercooling. Constructed to operate with residual fuels, its design includes wet iron cylinder liners, jet-cooled pistons, indirectly cooled valve seats, austenitic valves with hard facings, and valve rotators.

### Procedure

Acurex carried out a detailed study of the properties of the residual shale oil and found them to be considerably better than those of petroleum residual fuels. When heated to reduce viscosity, properties were much closer to those of No. 2 diesel fuel than those for residual fuels. The cetane number was measured at 47.8, and the calculated diesel index was 52.2.

The Ricardo engine test series included back-to-back tests to compare performance and emissions when firing shale residual fuel to those when firing No. 2 diesel fuel, a 115-hour endurance test, and a post-endurance test check of performance and emissions. In addition, measurements of cylinder pressure, injector needle lift, and fuel pressure were carried out in one cylinder.

The 115-hour endurance test was carried out following a cycle that included 1.5 hours at 1,000 rpm, 100 percent load, and 0.5 hours at 500 rpm, no load. It was felt that this would provide a high rate of deposit accumulation with a realistic amount of transient operation. At the start of each day the engine was started with No. 2 diesel fuel, and the engine was operated on No. 2 diesel fuel for 15 minutes at the end of each day. The engine was disassembled and inspected after the endurance test.

### Test Results

In initial performance tests it was found that performance with shale residual fuel was identical to that with No. 2 diesel fuel. Evaluation of fuel blends had been planned, but was not carried out because there was no performance difference between the two fuels. Inspection after eight hours of operation, however, showed considerable soft carbon on the fuel injector when firing shale residual fuel, leading to some concern about long-term operation.

Figure 14-1 shows cylinder pressures, fuel line pressures, and injector needle lift for operation with No. 2 diesel fuel and residual shale oil. The cylinder pressure trace is identical for the two fuels, and other traces reflect viscosity differences.

A 115-hour endurance test was interrupted after 60 hours by plugging of the unheated fuel filter with wax. A heater was added to the filter and the test completed without incident. The post-test performance data were obtained at the end of 100 hours, following which the remaining fuel was used to complete 115 hours of operation.

Figure 14-2 shows engine performance, and Figure 14-3 shows emission data for the APE-Allen engine. Data for both DF-2 and shale residual fuel are shown. The data before and after the endurance test were nearly identical.

Inspection of the engine after the endurance test showed no engine distress caused by shale residual fuel. Soft carbon deposits, which did not affect performance, were greater than for No. 2 diesel fuel.

### Conclusions

Conclusions, quoted from Reference 14-2, follow. (RSO is residual shale oil, and standard diesel fuel is No. 2 diesel fuel.)

- "o Laboratory tests showed low levels of corrosion and deposit-causing elements. Therefore, corrosion and wear of engine components, when using RSO, should be no worse than for standard diesel fuel.
- o The high wax content of RSO requires heating for supply, handling, and injection systems.
- o Laboratory tests showed that the cetane number of RSO was equivalent to No. 2 diesel; hence, no engine modifications should be needed to burn RSO. This was confirmed by the engine tests.
- o The engine performance on RSO was essentially similar to that for No. 2 diesel fuel. The thermal efficiency was slightly lower and Bosch smoke and particulates were slightly higher, especially at low load.
- o Soft carbon deposits, formed on injectors when using RSO, did not affect performance.
- o The 115-hour endurance test showed no significant performance deterioration. The deposit accumulation in combustion chambers and ports was not severe but was greater than standard diesel fuel would produce. Longer endurance tests are required to fully establish this conclusion."

### References

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TABLE 14-1. ANALYSIS OF RESIDUAL SHALE OIL  
USED IN TESTS OF BROWN BOVERI TYPE  
35 INDUSTRIAL GAS TURBINE(14-1)

Fuel source: Sohio Toledo Refinery

		ASTM D	
Specific Gravity 16/16C		1298	0.887
Distillation, Vol %	C	1160	
5/10			243/277
30/50			344/381
70/90			426/484
95/EP			510/530
Viscosity	cSt		
50 C		445	9.5
70 C			5.6
90 C			3.2
Pour Point,	C		35
Flash Point, FM,	C	93	99
Congeaing Point,	C	938	32
Aniline Point,	C	611	83
Cetane Index		976	69.0
Gross Heat of Combust.	Btu/lb	2382	19,453
Net Heat of Combustion	Btu/lb		18,282
	MJ/kg		42.52
Refractive Index		1218	1.4930
Molecular Weight		2503	350
Asphaltenes	wt %	IP-143	0.21
Carbon Residue,	wt %	189	0.12
Water and Sediment,	vol %	2709	0.05
Carbon	wt %		86.58
Hydrogen	wt %		12.96
Sulfur	(ppm)		(160)
Nitrogen	wt %		0.38
Oxygen	(ppm)		(700)
Ash	(ppm)	482	(20)
As/Fe	(ppm)		(0.03/7.1)
Na/K	(ppm)		(2.9/0.7)
V/Ni	(ppm)		(0.4/0.8)

TABLE 14-2. HYDROCARBON ANALYSIS OF RESIDUAL SHALE  
OIL USED IN TESTS OF BROWN BOVERI TYPE  
35 INDUSTRIAL GAS TURBINE(14-1)

Fuel source: Sohio Toledo Refinery

<u>Components, Wt %</u>	<u>Fractions</u>	<u>Totals</u>
n. Paraffins		12.0
C 15 - 18	1.6	
19 - 22	4.0	
23 - 27	3.8	
28 - 32	2.6	
Isoparaffins		4.7
Cycloparaffins		37.7
mono	10.7	
di	8.6	
tri	7.7	
tetra	5.8	
penta, (+)	4.9	
<u>TOTAL SATURATES</u>		<u>54.4</u>
Monoaromatics		17.7
Alkyl Benzenes	6.1	
Naphthene Benzenes	6.3	
Dinaphthene Benzenes	5.3	
Diaromatics		10.1
Naphthalenes	3.4	
Acenaphthenes	3.3	
Fluorenes	3.4	
Triaromatics		3.4
Phenanthrenes	2.5	
Naphth. Phenanthrenes	0.9	
Tetra and Higher		1.8
Aromatic Sulfur		0.6
<u>TOTAL AROMATICS</u>		<u>33.6</u>
SATURATES		54.4
AROMATICS		33.6
OLEFINS		3.9
POLAR COMPOUNDS		3.0
LOSS (in separation)		<u>5.1</u>
		100.0
<u>NMR Analysis of Aromatic Cut</u>		
Aromaticity (by C13)		0.37
Aromaticity (by Proton NMR)		0.39
• Arom. Ring Carbons/Molec.		10.4
Alkyl Substituents/Molec.		2.9
Ave. Carbon/Subst.		5.6

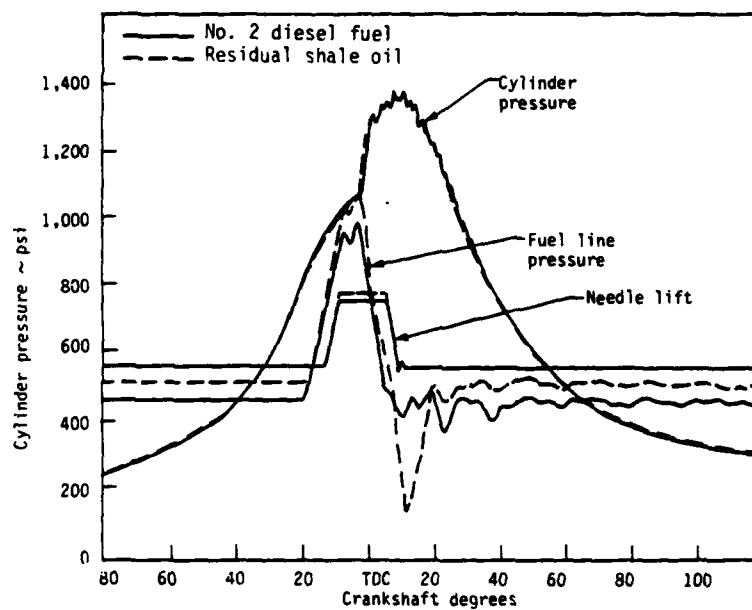


FIGURE 14-1. COMPARISON OF CYLINDER PRESSURE AND FUEL PRESSURE FOR APE ALLEN S300 DIESEL ENGINE WHEN BURNING NO. 2 DIESEL FUEL AND RESIDUAL SHALE OIL (14-2)  
(75 percent load, BMEP = 158 psi)

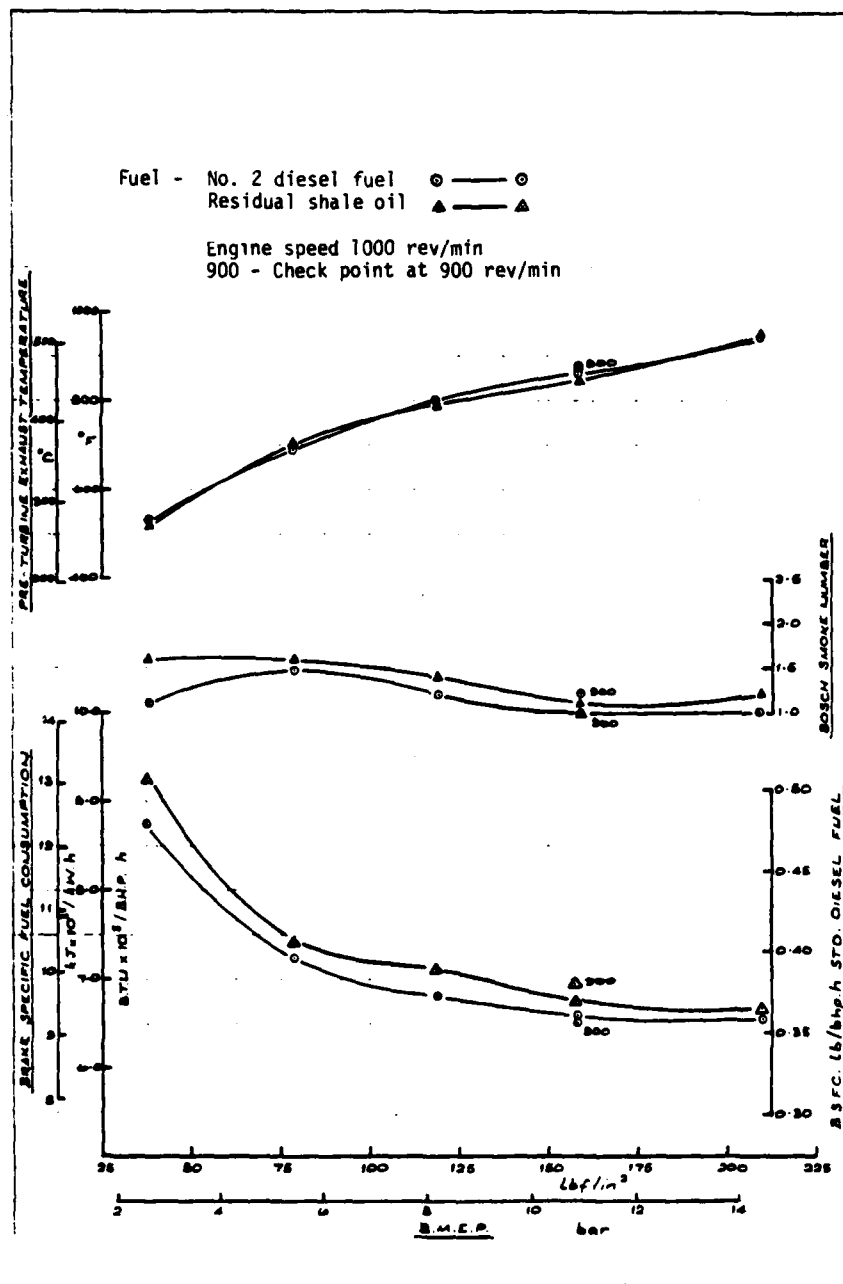


FIGURE 14-2. RESULTS OF PERFORMANCE TEST OF APE ALLEN S300 DIESEL ENGINE PRIOR TO ENDURANCE TESTS(14-2)

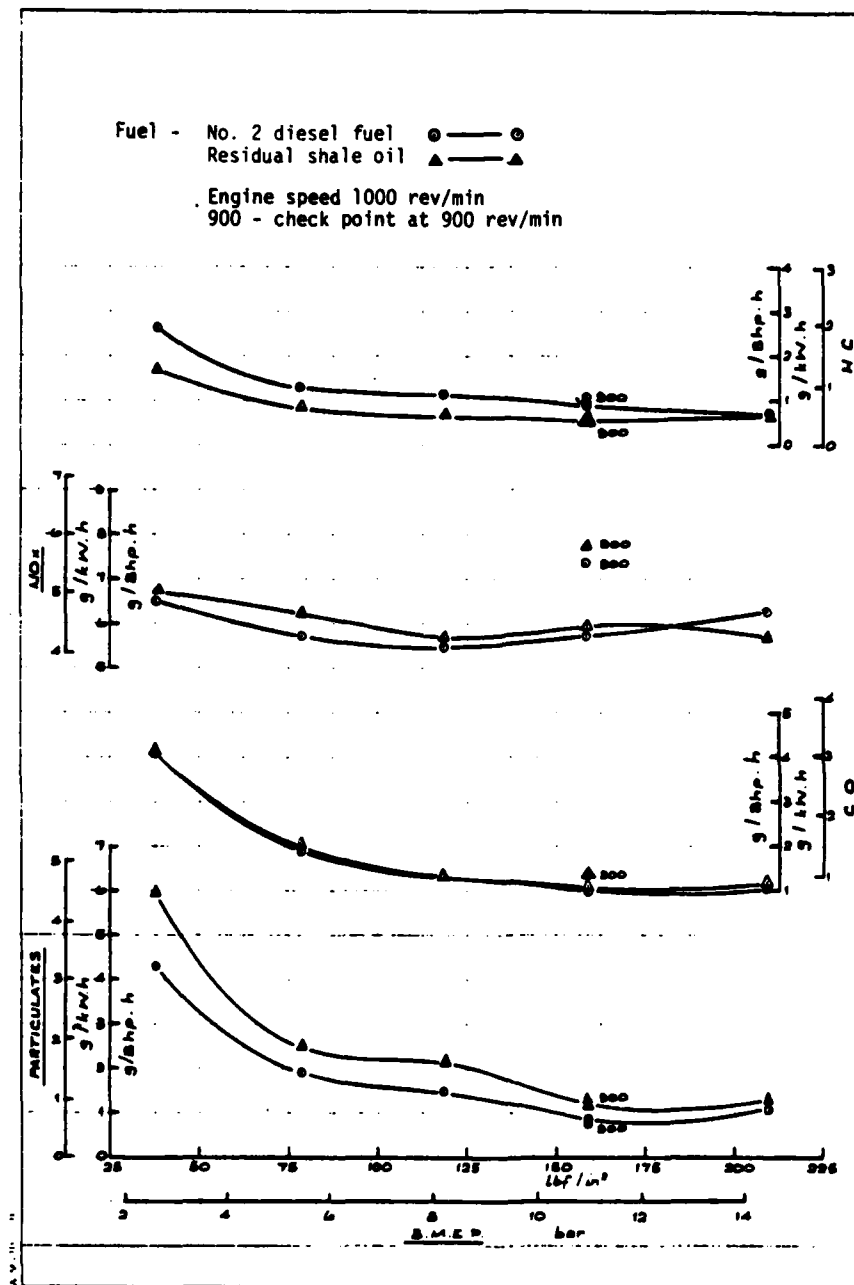


FIGURE 14-3. RESULTS OF EMISSION TEST OF APE ALLEN S300 DIESEL ENGINE PRIOR TO ENDURANCE TESTS(14-2)



## 15. CHEMICAL CHARACTERIZATION OF SHALE FUELS

### Introduction

This section presents information obtained by various investigators on the chemical characterization of shale derived DFM and JP-5. Additional data is presented in Section 2, Product Distribution and Analysis. Although some data presented earlier are repeated for clarity, an attempt was made to restrict this section to non-specification tests.

### Objectives

The objectives of the investigators described in this section were primarily directed toward: (1) the determination of the stability of the shale-derived fuels; (2) characterization of the organic composition of these fuels (aromatic versus aliphatic composition); and (3) the distribution of nitrogen-bearing compounds within the fuels. One investigation examined microbial degradation of DFM; another examined hydroperoxide formation in jet fuel. The former is related to a cause of accelerated corrosion of fuel tanks and/or potential plugging of fuel filters while the latter is associated with fuel incompatibility with elastomers. Finally, the compatibility of shale-derived fuels with petroleum fuels, metals, elastomers, coatings, and equipment components was investigated.

### Chemical Analyses

Chemical analyses in addition to those required to satisfy Military Specification MIL-F-16884G for DFM and MIL-T-5624K for JP-5 were performed by a number of groups. These analyses, and their significance, are discussed below.

### Elemental Analysis

Elemental analysis (carbon, hydrogen, nitrogen, sulfur, and oxygen) is routinely performed on fuels using a variety of analytical techniques. Several investigations of shale DFM and shale JP-5 included such analysis. Representative results from several of these investigations are presented in Table 15-1, Elemental Analysis of Shale-Derived DFM, and Table 15-2, Elemental Analysis of Shale-Derived JP-5. In general, these analyses are fairly consistent and in agreement with those reported by others.

The data for carbon and hydrogen content are in excellent agreement for both fuels among the various laboratories. The analysis for the minor constituents (nitrogen, sulfur, and oxygen) shows some variation; however, the variation is not significantly more than would

be anticipated. The variation in the nitrogen and sulfur concentration could be due to the analytical procedure used, differences in preparing the samples for analysis, or they may accurately reflect the decreasing activity of the hydrotreating catalyst noted during the refining operation. Frequently, oxygen concentration is not reported or is reported by difference in analyses of this type. The variation in oxygen concentration, then, is also within the range that could be expected.

Elemental analysis, by itself, is not a critical consideration for a fuel except for sulfur and, perhaps, nitrogen. Sulfur levels are, of course, directly related to emissions of  $\text{SO}_2$  resulting from combustion of the fuel. Similarly,  $\text{NO}_x$  emissions for gas turbines and boilers are influenced by, but not strictly related to the nitrogen content of the fuel. Sulfur, nitrogen, and oxygen levels appear to have an effect on fuel stability, although the form in which these elements exist within the fuel are probably more important than their absolute values. The elemental analysis can provide, by examining the ratio of carbon to hydrogen, or the hydrogen content, an indication of the combustion characteristics and projected engine life. The carbon to hydrogen ratio is useful in this manner by providing an indication of the aromatic content of the fuel.

#### Analysis for Organic Types

Most of the organic structural characterization on the finished shale JP-5 and shale DFM samples have been limited to measurement of the concentrations of various types of organic hydrocarbons such as saturates, olefins, and aromatics. The methods used include fluorescent indication analysis (FIA) and ASTM D-1319. One exception has been the report by Winnard and Burdett of the Union Oil Company of California<sup>(15-2)</sup> in which a mass spectroscopy-liquid chromatography procedure was used to measure types of compounds within the saturate and aromatic fractions. Each contractor used a slightly different analysis procedure, resulting in some confusion when the data from a single sample are compared because of the use of different ways of dividing the molecules by chemical type.

The analyses from each contractor are summarized in Table 15-3 for shale JP-5 and in Table 15-4 for shale DFM. Corresponding samples from the pilot plant and refinery runs are grouped together so that they can be compared. The presence of condensed ring structures in the processed fuels is of concern because large aromatic structures tend to produce soot in a turbine combustor, resulting in increased flame radiation. This increases combustor liner temperature and reduces combustor life.

Crude shale oil is considerably less aromatic than coal-derived synthetic crude or petroleum; however, a considerable amount of aromatics is present.

TABLE 15-1. ELEMENTAL ANALYSIS OF SHALE-DERIVED DFM

Element/Reference	15-1	15-2	15-3	15-4	15-5	15-6
Carbon, wt %	84.88	86.6	86.75	86.27	86.33	86.54
Hydrogen, wt %	12.78	13.4	13.02	13.28	13.67	13.36
Nitrogen, ppm	33	15	90	3.9	86	1
Sulfur, ppm	200	7	--	--	600	40
Oxygen, ppm	--	80	--	--	--	3700

TABLE 15-2. ELEMENTAL ANALYSIS OF SHALE-DERIVED JP-5

Element/Reference	15-1	15-2	15-3	15-4	15-5	15-6
Carbon, wt %	86.63	86.2	86.64	--	86.76	85.92
Hydrogen, wt %	13.76	13.8	13.68	--	14.24	13.68
Nitrogen, ppm	ND	0.5	8.3	--	15	1
Sulfur, ppm	400	15	1.3	--	500	50
Oxygen, ppm	ND	1100	53	--	--	3800

TABLE 15-3. SUMMARY OF ORGANIC STRUCTURE ANALYSES  
FOR SHALE JP-5 AFTER ACID/CLAY TREATMENT

Reference Number	15-3	15-5	15-1	15-4	15-1	15-4	15-2
<u>Sample</u> <sup>1.)</sup>	PP	PP	PP	PP	R	R	R
<u>Organic Structure Type</u>							
Saturates	80.0	(76.4) <sup>2.)</sup>	76		74		78.4
Paraffins	46.0			43.9		42.5	46.0
Naphthenes	33.1			33.1		36.0	
Mononaphthenes							24.3
Dinaphthenes							8.1
Olefins	0.0	0.7	1		2		
Aromatics	20.9	22.9	23	23.0	24	21.5	21.6
Alkyl benzenes							10.8
Indans-tetralins							10.8
Naphthalenes	0.2						

1.) PP = pilot plant, R = refinery.

2.) Not reported, calculated by difference.

TABLE 15-4. SUMMARY OF ORGANIC STRUCTURE ANALYSES  
FOR SHALE DFM AFTER ACID/CLAY TREATMENT

Reference Number	15-3	15-5	15-1	15-4	15-1	15-4	15-2
<u>Sample</u> <sup>1.)</sup>	PP	PP	PP	PP	R	R	R
<u>Organic Structure Type</u>							
Saturates	68.0	62.1	62		69		71.8
Paraffins	42.2			42.2		45.5	42.8
Napthenes	25.8			25.8		25.5	
Mononaphthenes							18.2
Polynaphthenes							10.8
Olefins	0.0	1.5	2		5		
Aromatics	32.0	36.4	36	32.0	26	29.0	28.2
Alkyl benzenes							8.1
Indanes tetraline							11.3
Dinaphthene benzenes							4.6
Naphthalenes							1.9
Biphenyls							1.2
Fluorenes							0.8
Phenanthrenes							0.3

1.) PP = pilot plant, R = refinery.

The MIL-T-5624K requirements for JP-5 specifies that aromatic and olefin content be limited to 25 and 5 volume percent, respectively. The combined averages reported for the pilot plant and refinery produced shale JP-5 samples are 22.2 percent aromatics and 0.9 percent olefins with no single analysis exceeding the specification limits. The shale JP-5 samples are approximately 77 percent saturates, 22 percent aromatics and 1 percent olefins.

The saturates have been divided into straight chain (paraffins) and cyclic (naphthenes) materials. Approximately 57 percent of the saturates are paraffins and 42 percent are naphthenes, mostly (75%) mononaphthenes. Almost all of the aromatics contain only one aromatic ring.

MIL-F-16884G specifications for DFM do not include any limits on hydrocarbon type. The finished shale DFM samples consist of 67 volume percent saturates, 2 percent olefins, and 31 percent aromatics. The saturates in the DFM samples, which are higher molecular weight materials, contain 63 percent paraffins and 57 percent naphthenes, of which 63 percent are single-ring and 47 percent are two-ring compounds. The aromatics consist of 85 percent single-ring, 14 percent two-ring and 0.5 percent three-aromatic-ring compounds.

#### Storage Stability

Resistance to the formation of insoluble material in the fuel during storage is required for long-term storage of Navy fuels. Therefore, the DFM specification includes a measure of the potential instability, specifically ASTM D2274 for Oxidation Stability of Distillate Fuel Oil (Accelerated Method). In this test, 350-ml samples of filtered fuel are placed in large test tubes which are kept at 95° C (203°F) for 16 hr with oxygen bubbling through the fuel at 3 l/hr. Totals of insolubles are determined when the samples have cooled. The diesel fuel specification, MIL-F-16884G, Diesel Fuel Marine, requires that the total insolubles not exceed 2.0-mg/100 ml fuel.

Unfortunately, the reproducibility of Method D2274 is poor, and several test programs to assess the reproducibility of the method between laboratories have had disappointing results. Generally, the method is successful in identifying unstable fuels. To supplement the D2274 results, several stability tests at lower temperatures and of longer duration were included in the synfuels characterization program. These long-term tests serve as a check on the results from Method D2274, a necessary precaution until more experience with the stability behavior of nonpetroleum fuels has been obtained.

One of these lower temperature stability tests is a reference test developed by E. W. White of DTNSRDC for diesel fuel stability.<sup>(15-7)</sup> In this test, samples are stored for three years at ambient temperature in one-gallon Pyrex bottles. The validity of the gallon-bottle storage test is based on extensive comparisons of storage

column tests at ambient temperature. Two disadvantages are inherent in the gallon-bottle tests. First, the large quantity (about 8 gal) of fuel required is a handicap. For this reason, a similar test based on storage in one-quart Pyrex bottles was run concurrently with the one-gallon bottles in ambient outdoor storage.

The second disadvantage is that three years is required to complete both these bottle tests. In an effort to develop a valid accelerated test, the 36-week beaker test at 100°F (43°C) was included in the synfuel test program. Unfortunately, excessive amounts of some fuels evaporated from the beakers during the test. Consequently, the beaker test was modified by using Pyrex bottles with screw cap lids to minimize evaporative losses, and mild steel wire was added for better simulation of tank storage.

These long-term bottle storage tests and intermediate-term beaker tests are unsuitable for specification inspection tests which must be completed in a matter of hours. However, it is important to include the longer term stability tests in the synfuels program to establish that these nonpetroleum fuels do not differ significantly from petroleum fuels in storage stability behavior. Such data are needed also for correlation with the DFM specification 16-hr test.

The procedures for each of the three storage stability tests examined at the David W. Taylor Naval Ship Research and Development Center are given below. The last procedure, ASTM D2274, is included for reference only. Results of tests conducted with this procedure are reported in the section discussing specification tests.

#### Bottle Storage

Fuel samples are filtered through 100-mesh stainless steel screens into clean one-gallon or one-quart size Pyrex glass bottles which are wrapped in aluminum foil to prevent exposure of the fuel to light. A coil of mild steel wire is immersed in the fuels to simulate steel tank storage. The bottled samples are stored outdoors at ambient temperature for periods as long as 36 months. Bottles are withdrawn from storage after 3, 6, 12, 18, 24, 30, and 36 months and the fuel is examined for filterable insolubles, adherent insolubles, total insolubles, TAN, IFT, and viscosity. The insolubles are determined by an adaption of the ASTM D2274 technique.

#### Beaker Storage

In the regular beaker storage test the fuels are filtered through 100-mesh stainless steel screen to remove heterogeneous contaminants. A 500-ml sample of fuel is placed in each of four clean 600-ml beakers, which are covered with watch glasses and vinyl-wrapped to retard evaporation. The beakers then are placed in an oven at 43.3°C (110°F). Samples are removed after 1 day, 12 weeks, 24 weeks, and 36

weeks for determination of total insolubles and TAN. In addition, IFT and viscosity are determined on the 36-week samples.

In the modified beaker storage test, which is similar to the standard beaker storage test, 32-oz wide mouth screw cap glass jars are used instead of beakers. In addition, a 20-cm length of 1/16-in mild steel wire is submerged in the fuel sample. The jars are cooled to room temperature every two weeks and the caps are loosened to allow air to contact the samples. The fuel samples are examined at the specified intervals for filterable insolubles, adherent gum, and total insolubles. The TAN is measured after 12-, 24-, and 36-weeks' storage. Viscosity and IFT are measured at 36 weeks.

#### ASTM D2274 Accelerated Storage Test

A 350-ml aliquot of filtered fuel is placed into a large test tube, 600-mm high by 45-mm O.D., fitted with a water-cooled condenser and an oxygen delivery tube. The test tube is kept at 95 C (203 F) for 16 hr. The sample is allowed to cool in the dark to 22 C to 27 C before determining the insolubles present. Other measurements of stability parameters are made as specified.

Tables 15-5 through 15-9 present White's results of bottle and beaker storage stability tests of shale JP-5 and shale DFM. Storage stability of both shale fuels was adequate.

The three fuels obtained from shale oil (DFM, JP-5, and JP-8) were also subjected to stability tests at 43 C for 32 weeks. (15-6) After 4, 8, 16, and 32 weeks, pairs of bottles were removed from storage and analyzed separately for gum content, dissolved oxygen, and peroxide number. Twelve unvented bottles of each sample were originally placed in storage and each bottle was opened every 4 weeks. As the pairs were removed, they were filtered through glass sintered filters. The filtered fuel was measured for gum content by ASTM D 381. The bottles were rinsed with a triple solvent (equal volumes of toluene, acetone, and methanol) to dissolve adherent gum. The rinses from both bottles were poured through the same glass sintered filters to dissolve any of the same type of fuel-insoluble gum that may have remained suspended in the fuel and filtered out during the first filtration. Vaporization of the triple solvent followed, and the insoluble gum was recovered and weighed. Any additional material that remained on the glass sintered filter was then measured by reweighing the filter. The results of the storage stability test are shown in Table 15-9. The finished fuels manufactured from shale crude oil were stable throughout the 32 weeks of storage at 43 C. Only small amounts of gum were formed in each sample.

Dissolved oxygen content and peroxide numbers of the stored samples were measured after 4, 8, 16, and 32 weeks. The data are shown



TABLE 15-5. INSOLUBLES FORMED DURING STORAGE  
IN ONE-GALLON BOTTLES (15-7)

Storage Time (Months)	Shale DFM		
	Filterable (mg/100 ml)	Adherent (mg/100 ml)	Total Insolubles (mg/100 ml)
Initial	0.03	0.0	0.03
3	0.06	0.01	0.07
6	0.05	0.09	0.14
12	0.45	0.19	0.64

Storage Time (Months)	Shale JP-5		
	Filterable (mg/100 ml)	Adherent (mg/100 ml)	Total Insolubles (mg/100 ml)
Initial	0.07	0.00	0.07
3	0.03	0.02	0.05
6	0.05	0.07	0.12
12	0.08	0.22	0.30

TABLE 15-6. INSOLUBLES FORMED DURING STORAGE  
IN ONE-QUART BOTTLES (15-7)

Storage Time (Months)	Shale DFM		
	Filterable (mg/100 ml)	Adherent (mg/100 ml)	Total Insolubles (mg/100 ml)
Initial	0.09	0.0	0.09
3	0.09	0.02	0.11
6	0.14	0.06	0.20
12	0.20	0.04	0.24

Storage Time (Months)	Shale JP-5		
	Filterable (mg/100 ml)	Adherent (mg/100 ml)	Total Insolubles (mg/100 ml)
Initial	0.09	0.00	0.09
3	0.13	0.07	0.20
6	0.17	0.09	0.26
12	0.10	0.10	0.20

TABLE 15-7. TOTAL ACID NUMBER FOUND DURING  
BOTTLE STORAGE (15-7)

Container Size	Storage Time	TAN Fuel (mg KOH/g)	
		Shale DFM	Shale JP-5
One Gallon	1 Day	0.020	0.000
	12 Months	0.003	0.006
One Quart	1 Day	0.020	0.000
	3 Months	0.020	0.020
	12 Months	0.025	0.025

TABLE 15-8. TOTAL INSOLUBLES FORMED DURING  
BEAKER STORAGE (15-7)

Storage Time, Weeks	Total Insolubles Shale DFM		Total Insolubles Shale JP-5	
	Beaker (mg/100 ml)	Modified Beaker (mg/100 ml)	Beaker (mg/100 ml)	Modified Beaker (mg/100 ml)
Initial*	0.25	0.00	0.16	0.00
12	0.11	0.05	0.02	0.02
24	0.14	0.06	0.12	0.02
36	0.20	0.40	0.18	0.44

\*After 1 day.

TABLE 15-9. STORAGE STABILITY TESTS 43°C (15-6)  
mg/100 ml

Description	Initial	4 weeks			8 weeks		
		Soluble gum	Insoluble gum	Precipitate	Soluble gum	Insoluble gum	Particulate
JP-8 from Paraho II Shale Oil	0.4	A-1.2 B-1.2	0.7 0.5	0.1 0.1	A-0.9 B-0.9	0.6	0.1
JP-5 from Paraho II Shale Oil	0	A-0 B-0	0.5	0.1	A-0 B-0	0.4	0.1
DFM from Parahoo II Shale Oil	0	A-0 B-0	0.6	0.6	A-0.6 B-0.5	0.9	1.0

Description	Initial	16 weeks			32 weeks		
		Soluble gum	Insoluble gum	Precipitate	Soluble gum	Insoluble gum	Particulate
JP-8 from Paraho II Shale Oil		A-1.1 B-1.0	1.0	0.2	A-1.7 B-1.7	2.3	0.3
JP-5 from Paraho II Shale Oil		A-0 B-0	0.7	0.6	A-0 B-0	0.8	0.2
DFM from Paraho II Shale Oil		A-0 B-0	0.9	1.0	A-0.5 B-1.2	1.4	1.0

in Table 15-10. The shale fuels oxygen content remained at approximately the same level for 16 weeks of storage. At 32 weeks, the dissolved oxygen levels were reduced significantly, indicating that oxidation products began being formed somewhere between the 16th to 32nd weeks. The shale fuels showed no measurable peroxide number until 8 weeks of storage and slight increase in value after 16 and 32 weeks. The 16-week samples for the shale JP-8 fuel were lost before peroxide numbers were measured.

### Thermal Stability

In the fuel delivery systems of jet aircraft, the fuel encounters rather high temperatures before it enters the combustion zone. The need to predict the thermal stability, or resistance to oxidation at elevated temperature, culminated in the development of the JFTOT (Jet Fuel Thermal Oxidation Tester). This device estimates the ability of jet fuels to resist thermal and oxidative degradation as indicated by the color of the deposit produced on a heated surface and by the change in pressure drop for the passage of the fuel through a test filter. The ASTM D3241 method uses the JFTOT to rate the "tendencies of gas turbine fuels to deposit decomposition products in the fuel system."

The JP-5 fuel, MIL-T-5624 or NATO F-44, the Navy's high flash-point, kerosine type aviation turbine fuel, is an "Acceptable Substitute Fuel" for DFM (MIL-F-16884 or NATO F-76) for all Navy vessels. Use of the JP-5 JFTOT criteria to evaluate diesel fuels was, therefore, considered as a starting point in detecting fuels which could cause plugging of fuel filters, valves, and nozzles because of inadequate thermal or oxidative stability.

Table 15-11 summarizes results of thermal oxidation stability tests by the JFTOT procedure conducted by Southwest Research.<sup>(15-6)</sup> The data indicate that these fuels are thermally stable. The jet fuels met the specification requirements. The DFM had a visual tube rating of 3, which would be a failure for jet fuels although it is still a good rating. After storage, the DFM had a visual rating of 1, implying most of the unstable species had been removed as gum.

White ran the six runs at different temperatures for each fuel at the David W. Taylor Naval Ship Research and Development Center.<sup>(15-7)</sup> The test data are summarized in Table 15-12.

The MIL-T-5624 specification for JP-5 fuel requires that the pressure drop ( $\Delta P$ ) not exceed 25 mm across the filter in the JFTOT test when the fuel is circulated for 150 minutes with the heater tube at 260 C (500 F). The standard JP-5 fuel passed this specification test, as would be expected. The shale JP-5, Fuel B, also passed with no perceptible pressure drop. Although this test is not a requirement in the DFM specification, six of the eight DFM fuels qualified with little or no  $\Delta P$  at 260 C. The shale DFM also showed no significant pressure drop under these conditions.

TABLE 15-10. DISSOLVED OXYGEN AND PEROXIDE NUMBERS IN FUELS STORED AT 43 C (15-6)

Description	Initial		4 Weeks		8 Weeks	
	Dissolved O <sub>2</sub> , ppm	Peroxide Number*	Dissolved O <sub>2</sub> , ppm	Peroxide Number*	Dissolved O <sub>2</sub> , ppm	Peroxide Number
JP-8 from Paraho-II Shale Oil	69	0	67	0	67	0.14
JP-5 from Paraho-II Shale Oil	72	0	69	0	60	0.06
DFM from Paraho-II	54	0	52	0	52	0.33

Description	16 Weeks		32 Weeks	
	Dissolved O <sub>2</sub> , ppm	Peroxide Number*	Dissolved O <sub>2</sub> , ppm	Peroxide Number*
JP-8 from Paraho-II Shale Oil	**	**	45	0.24
JP-5 from Paraho-II Shale Oil	85	0.12	42	0.16
DFM from Paraho-II Shale Oil	46	0.35	34	0.39

\* Peroxide number is defined as the gram-equivalent of active oxygen in 1000 liters of fuel.

\*\* Sample lost.

TABLE 15-11. THERMAL OXIDATION STABILITY (JFTOT) DATA FOR SHALE-DERIVED FUELS BEFORE AND AFTER 32 WEEKS OF STORAGE AT 43°C (15-6)

JFTOT at 260°C	JP-8	JP-5	DFM
As Received	0	0	0
P, mm Hg	2	1	3
Tube rating, visual	10.0	2.0	11.5
Tube Deposit Rating, spun	12.0	8.0	14.0
After 32 weeks at 43.3°C			
P, mm Hg	0	0	0
Tube rating, visual	2	1	1
Tube Deposit Rating, spun	2	4	7
Tube Deposit Rating, spot	7.5	6	14

TABLE 15-12. RESULTS OF JET FUEL THERMAL OXIDATION TESTS (15-7)

Fuel	Temperature (°C)	P at 150 Minutes (mm Hg)	Tube Deposit Rating	D1500 Color	
				Before	After
<u>Jet Fuels</u>					
A (JP-5)	260	6	L1**	L0.5	...
	280	248/139*	L1	L0.5	...
	300	250/105*	3	L0.5	...
B (Shale JP-5)	260	0	0	1.0	1.0
	280	1	0	1.0	1.0
	300	30	4	1.0	1.0
<u>Petroleum DFM Samples</u>					
C (DFM)	230	2	L4	1.5	L2.0
	240	21	4	1.5	2.0
	245	40	4	1.5	L2.5
	260	250/52*	4	1.5	2.5
	D (DFM)	240	1	0	0.5
260		2	4	0.5	L1.0
270		23	4	0.5	L1.0
280		250/100*	4	0.5	L1.0
E (DFM)	260	0	L1	0.5	0.5
	280	2	3	0.5	0.5
	290	2	4	0.5	L1.0
	300	125	4	0.5	L1.0
F (DFM)	260	1	L3	0.5	0.5
	280	0	4	0.5	L1.0
	300	41	4	0.5	1.0
G (DFM)	250	2	L4	1.0	...
	260	1	4	1.0	L1.5
	280	2	4	1.0	L1.5
	290	1	4	1.0	L1.5
	305	1	4	1.0	L1.5
	320	11	4	1.0	L1.5
H (DFM)	260	1	4	L1.5	L1.5
	280	1	4	L1.5	L1.5
	300	2	4	L1.5	1.5
	320	1	4	L1.5	1.5



TABLE 15-12 (Continued)

Fuel	Temperature (°C)	$\Delta P$ at 150 Minutes (mm Hg)	Tube Deposit Rating	D1500 Color	
				Before	After
I (DFM)	260	0	4	L1.0	L1.0
	280	1	4	L1.0	L1.5
	300	25	4	L1.0	L1.5
J (DFM)	240	1	4	L1.5	L1.5
	250	3	4	L1.5	L1.5
	260	154	4	L1.5	L1.5
<u>Shale DFM Sample</u>					
K (Shale DFM)	260	1	L1	0.0	0.0
	280	2	L2	0.0	0.0
	300	0	L3	0.0	0.0
	320	1	3	0.0	0.0

\*Time from start of run to reaching 250 mm Hg pressure, in minutes

\*\*L = Lighter than the indicated color.

Examination of the heater tube deposit ratings for the fuels given in Table 15-12 shows that all but two of the DFM fuels developed a rating of 4 or higher at 260°C. A rating of 3 or higher is unacceptable for a JP-5 fuel. The standard JP-5 fuel had a rating of L1 which is in the low range. Both of the shale fuels performed very well in this aspect of the JFTOT test. The shale JP-5 and the shale DFM have readings of zero and one, respectively. This may result in part from rather severe hydrogenation of the shale fuels during manufacture.

The depth of color of the fuels was measured by ASTM Standard Method D1500 before and after each JFTOT test. These data are contained in Table 15-12 also. In all cases there was little or no color change in the fuel as a result of the JFTOT exposure.

### Mechanisms of Fuel Stability

It is generally acknowledged that autoxidation in hydrocarbon liquids is a chain reaction involving peroxy and hydrocarbon free radicals. There is a period in this process during which little oxygen is absorbed and only small amounts of oxidation products are formed. After this induction period, peroxides are formed, followed by insoluble oxidation products. (15-6)

Compounds containing heteroatoms, particularly nitrogen compounds, have been indicated in fuel instability behavior. Unfortunately, uncertainty arises from the fact that the chemical reactions involved in sediment formation are not identical for all fuels. Even when considering a single fuel, different modes of sediment formation may predominate at different storage temperatures. It appears that relatively non-basic heterocyclic nitrogen compounds, particularly those which contain alkyl groups in certain positions, may be the most troublesome; however, in some fuels, it is possible that basic nitrogen compounds may play a significant role. (15-18)

The Naval Research Laboratory is conducting a study to develop accelerated storage stability tests and to identify the effects of nitrogen compounds on the stability of middle distillate fuels. (15-8) Although the mechanism of sediment formation has not yet been determined, it was shown that 2,5-dimethylpyrrole (DMP) undergoes a rapid autoxidative self-condensation reaction in shale-derived fuels to form a high melting, largely insoluble sediment. Other nitrogen compounds, in particular other pyrroles, will promote the formation of significant amounts of insoluble material. These compounds would promote sediment formation even in the presence of an antioxidant additive. An indole (3-methylindole) was found to be a potent sediment promoter in the absence of the antioxidant additive. Basic nitrogen compounds appear to be less important in sediment formation.

These studies indicate that total nitrogen content of a fuel is a poor indicator of stability behavior. The isolation and identification of nitrogen compounds from shale-derived fuels of differing

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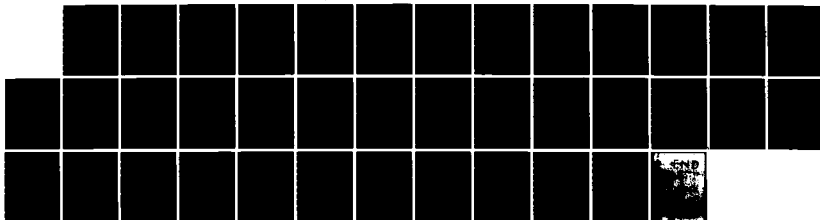
JOINT DOD/DOE SHALE OIL PROJECT VOLUME 3 TESTING OF  
REFINED SHALE OIL FUELS(U) BATTELLE COLUMBUS LABS OH  
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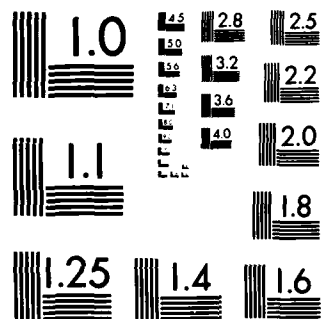
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storage stability is needed. Potential problem molecules in these fuels will need to be examined for oxidative stability to determine methods of processing shale oil and to develop new antioxidants if the problem molecules cannot be effectively removed.

#### Distribution of Nitrogen Compounds in Shale Crude and Products

Laramie Energy Technology Center (LETC) of the U.S. Department of Energy analyzed crude shale oil, Sohio hydroprocessed shale oil, LETC batch hydroprocessed shale oil, and various products from the hydroprocessed oils. These studies had two primary objectives: (1) develop suitable analytical techniques for determining the nitrogen compound distribution in the materials of interest and (2) determine the susceptibility of the nitrogen compound types to hydrodenitrogenation. This information, in addition to an understanding of which nitrogen compound types are most detrimental to fuels, could help select optimum refinery hydroprocessing conditions. Four references by Holmes (15-9, 10, 11, and 12) were reviewed.

The crude shale oil and each hydrotreated shale oil product were separated into six compound-type fractions by basic and neutral alumina and silica gel adsorption chromatography. These six fractions were named for characteristic compound types: hydrocarbon, pyridine I, pyrrole, pyrrole/arylamine, pyridine II, and amide/pyridine III. Table 15-13 presents the weight distribution of the compound type fractions in each material evaluated.

Each fraction was analyzed for elemental nitrogen, nitrogen compound type by infrared spectrometry and high resolution mass spectrometric analysis, and differential potentiometric titration analysis to determine relative basicities. Table 15-14 shows the nitrogen compound distribution as determined by those techniques.

The susceptibility of various nitrogen compounds to hydrodenitrogenation is determined by comparing the nitrogen distributions in the crude and hydroprocessed shale oils. Commercial-scale refining reduced the total nitrogen content in crude shale oil by 80 percent. The nitrogen types whose concentrations were decreased more than 80 percent were more susceptible to hydroprocessing, and those types that were decreased less than 80 percent were less susceptible to hydroprocessing and/or included contributions from nitrogen compound interconversions. The presence of certain nitrogen types in the hydroprocessed oil but not in the crude oil indicated formation of nitrogen compound intermediates during hydrodenitrogenation.

The ease of hydrodenitrogenation may depend upon the nitrogen compound type and its base strength. Nitrogen base types are removed most readily in the following order: very weak base, nonbasic, weak base II, weak base I. Holmes<sup>15-11</sup> found that nitrogen base type removal

TABLE 15-13. COMPOUND-TYPE FRACTIONATION RESULTS (15-9 and 15-11)

	Weight Percent of Sample				
	Crude (Paraho)	LETC(a) Hydrotreated Whole	SOHIO Hydrotreated Whole	Residuum(b)	DFM(b)
Hydrocarbon	31.7	77.6	81.6	89.1	93.1
Pyridine I	16.9	7.71	2.84	2.69	2.05
Pyrole	3.56	2.43	0.48	0.33	0.56
Pyrrone/Arylamine	5.47	1.03	2.54	2.03	0.31
Pyridine	1.92	2.91	2.88	4.21	0.94
Amide/pyridine III	20.8	1.09	0.45	0.47	0.35

(a)Batch hydrotreated

(b)Derived from SOHIO hydrotreated shale oil at refinery

TABLE 15-14. NITROGEN COMPOUND DISTRIBUTION (15-9 and 15-11)

Nitrogen compound types <sup>a</sup>	Nitrogen (wt% of sample)				
	Crude (Paraho)	Hydrotreated Whole	SOHIO Hydrotreated	Residuum	DFM
Strong base Alkylamines/alkylpiperidines	-	0.008	0.001	-	0.001
Weak base I Hindered alkylpyridines/alkylquinolines	0.152	0.113	0.098	0.090	0.124
Less hindered alkylpyridines/alkylquinolines/alkylacridines	0.532	0.107	0.144	0.165	0.063
Less hindered alkylpyridines/alkylquinolines/alkylhydroxyindoles <sup>b</sup>	0.241	0.021	0.013	0.008	0.016
Weak base IIC Alkylmaphthenopiperidines	-	0.009	0.004	0.04	0.003
Unknown	0.016	0.007	0.004	0.001	0.006
Weak base IId Alkylanilines/alkynaphthoanilines	-	0.012	0.002	0.003	0.015
Very weak base Alkylhydroxyindoles	0.423	0.005	0.022	0.004	0.010
Alkylpyrroles/alkylindoles	0.061	0.044	0.029	-	0.010
Unknown	0.032	0.017	-	-	0.010
Non-basic N-Alkylcarbazoles	0.022	0.002	0.030	0.003	-
Alkylpyrroles/alkylindoles/alkylcarbazoles/alkylbenzocarbazoles	0.167	0.060	0.084	0.078	trace
Alkylcarboxamides/alkyldiazaaromatics	0.546	0.004	0.010	0.014	0.281
Total	2.192	0.413	0.441	0.413	0.298

<sup>a</sup>All naphtho derivatives are not listed, but they are assumed to be present with the appropriate parent nitrogen compound type.

<sup>b</sup>Alkylhydroxyindoles were not found in the crude shale oil or JP-8.

<sup>c</sup>Titration in acetic anhydride. The nitrogen types do not acetylate.

<sup>d</sup>Titration in acetonitrile. These nitrogen types acetylate in acetic anhydride.

by one-pass, bench-scale hydroprocessing followed a similar order. Because of accumulative error in the data, the susceptibility of different nitrogen base types to hydrodenitrogenation cannot be determined definitively. The results indicate that nitrogen removal is independent of a compound's basicity and/or that nitrogen compound intermediates contribute to basicity values as less basic nitrogen compounds are converted to more basic compound types during hydrogenation.<sup>15-9</sup> Alkyl-substituted nitrogen compound types are removed most readily in the following order: unknown very weak base, carboxamides, hydroxypyridines, less hindered pyridines/quinolines/hydropyridines, unknown weak base II, less hindered pyridines/quinolines/acridines, pyrroles/indoles/carbazoles/benzocarbazoles, hindered pyridines/quinolines. The results indicate that amide-type compounds are more easily hydrodenitrogenated than less hindered pyridinic compounds, pyrrolic compounds and hindered pyridinic compounds. The order of nitrogen compound type removal should be noted with caution because of contributions from nitrogen compound interconversions. Similar nitrogen compound type susceptibility to hydrodenitrogenation by one-pass, bench-scale hydroprocessing (non-recycle) was found by Holmes<sup>15-11</sup>. However, smaller amounts of nitrogen compound intermediates and greater amounts of unreactive compounds were found in the commercial-scale hydroprocessed whole oil because of steady-state conditions approached during residuum recycle.<sup>15-9</sup>

### Compatibility Tests

#### Compatibility with Petroleum Fuels(15-13)

The compatibility of shale-derived fuels with petroleum fuels under conditions designed to accelerate the oxidation process was investigated. Blends of equal quantities of the shale JP-5 with petroleum JP-5, and the shale DFM with petroleum DFM were subjected to stability tests at 150 C and 80 C.

The High Temperature Stability of Distillate Fuels is a procedure being considered by ASTM for standardization and is summarized as follows: A measured volume of distillate fuel is aged 1.5 hours at 150 C in an open tube with air exposure. After aging and cooling, fuel is filtered and the amount of insoluble residue formed is estimated by determining the light reflectance of the filter pad. In this work, the procedure was modified to include a gravimetric determination of the residue, measurement of light absorbance of the fuel at four wavelengths, and steam jet gum on the fuel after aging and filtering. In addition, the adherent gum remaining in the sample aging bottles was measured.

The data for shale JP-5 evaluations are shown in Table 15-15 and indicate that no compatibility problems were observed with these two fuels when filterable particulates formed at 150 C are the criteria for consideration. The levels of particulates formed in the blended fuel



TABLE 15-15. COMPATIBILITY OF SHALE AND PETROLEUM JP-5 FUELS  
Modified 150°C Test

Fuel Description Test hr	Shale JP-5		Petroleum JP-5		Blend 50/50	
	1.5	3.0	1.5	3.0	1.5	3.0
Color after test, D 1500 (1)	0.5	0.5	0.5	0.5	0.5	0.5
Glass Fiber Filter Rating, Visual (2)	1	5	15	19	12	15
% Reflectance (3)	93.9	86.0	50.8	32.0	68.8	55.0
Wt of particulates, mg/100 ml	0.08	0.12	0.56	1.04	0.26	0.48
Light Absorbance,						
650 nm	0	0	0	0	0	0
575 nm	0	0.002	0	0.004	0	0
540 nm	0.001	0.007	0.006	0.015	0.001	0.005
500 nm	0.002	0.019	0.015	0.035	0.005	0.012
Adherent Insolubles, mg/100 ml	0.2	0.2	0.1	0.2	0.2	0.3
Steam Jet Gum on filtered sample, mg/100 ml	0.4	1.6	1.6	3.2	3.6	4.8

(1) Color of original samples and blends: 0.5  
 (2) Visual rating for all control filters: 1  
 (3) % Reflectance for all control filters: 99.0%

are about midway between the level formed in the shale JP-5 and in the petroleum JP-5. Fewer particulates were formed in the shale JP-5 than in the petroleum JP-5. The steam jet gum measured on the filtered fuels was slightly higher in the blend than in either the shale or petroleum JP-5.

Evaluations of DF-2, shale DFM, and 50/50 blends in the 150 C modified stability test are presented in Table 15-16. As in the case of JP-5 fuels, the level of particulates formed in the blended fuel samples was somewhere between the level formed in each fuel. The shale DFM produced less particulates than the DF-2. Steam jet gum measurements on the filtered blended fuel samples were considerably higher than those for the individual fuels. The higher steam jet gum values for the blends of JP-5 and DF-2 may indicate some synergism between shale oil and petroleum products during oxidation reactions under these aging conditions.

The 80 C Accelerated Fuel Oil Stability Test is a method developed by an additive manufacturer's petroleum laboratory to determine the stability of distillate fuels such as home heating oils or diesel oils under accelerated conditions within 7 to 14 days. The sample is aged at 80 C for up to 14 days, cooled and vacuum filtered through a filter paper to collect residues. The filter pad is compared to a set of standards to obtain a numerical visual rating or is rated by a reflectance rating. At AFLRL the method was modified so that residues were weighed and the fuel samples were examined for light absorbance in a UV-visible spectrophotometer at 650, 575, 540, and 500 nm. In addition, the samples were analyzed for adherent gum in the aging containers and exsistant gum content by the steam jet procedure.

Data for the stability tests of JP-5, shale JP-5, and a 50/50 blend of these two fuels at 80°C for 3, 7, and 14 days are shown in Table 15-17. Under these conditions, the stability of shale JP-5 was poor when compared to the data for JP-5. The blend of the two fuels gave results comparable to or even better than those for JP-5. Repeat tests for 7 and 14 days of the shale JP-5 were conducted and gave about the same results as the original tests. The stability test results at 80 C for the shale DFM, the DF-2, and a blend of these two fuels, for 3, 7, and 14 days, are shown in Table 15-18. As in the case of JP-5 fuels, the shale DFM gave poorer results than the DF-2, and the blend gave comparable or slightly better results than the DF-2. Repeat tests on the shale DFM for 7 and 14 days gave about the same results as the first tests. There appears to be no compatibility problem under these conditions between the shale and petroleum fuels; however, it is apparent that the shale-derived fuels oxidized more rapidly at 80 C than at 150 C or at 43 C.

TABLE 15-16. COMPATIBILITY OF SHALE AND PETROLEUM DIESEL FUELS  
Modified 150 C Test

Fuel Description Test hr	Shale DFM		Petroleum DF-2		Blend 50/50	
	1.5	3.0	1.5	3.0	1.5	3.0
Color D 1500 before test	0.5	0.5	1.5	1.5	1.0	1.5
after test	0.5	0.5	1.5	1.5	1.0	1.5
Glass Fiber Filter Rating, Visual (1)	1	2	17	20	8	20
% Reflectance	95.8	94.1	40.5	18.5	79.0	27.5
Filter	99.0	97.8	95.0	96.0	95.0	95.1
Control						
Wt of particles, mg/100 ml	0.06	0.16	0.59	0.90	0.24	0.59
Light Absorbance,						
650 nm	0	0.001	0.004	0.008	0	0.004
575 nm	0	0.008	0.023	0.031	0.011	0.019
540 nm	0	0.016	0.043	0.057	0.019	0.034
500 nm	0	0.035	0.088	0.114	0.040	0.067
Adherent Insolubles, mg/100 ml	0.2	0.2	0.2	0.2	0.1	0.2
Steam Jet Gum on filtered sample, mg/100 ml	1.2	3.8	4.0	4.2	16.0	13.6

(1) Visual rating for all control filters: 1

TABLE 15-17. COMPATIBILITY OF SHALE AND PETROLEUM JP-5 FUELS--MODIFIED 80 C OXIDATION TEST

Fuel Description Test Days	Shale JP-5		Petroleum-Based JP-5		50/50 Blend	
	3	7	14	3	7	14
Color, D 1500, Before/After	0.5/0.5	0.5/0.5	0.5/3.5	0.5/0.5	0.5/0.5	0.5/0.5
Repeat test	---	0.5/0.5	0.5/3.0	---	---	---
Glass Fiber Filter Rating						
Visual - Top/Control	2/1	7/1	20/1	6/2	11/3	13/2
Repeat test	---	20/4	19/1	---	---	---
% Reflectance - Top/Control	91.2/98.5	79.5/100	0/98.0	83.9/93.0	70.9/87.0	52.2/90.9
Repeat test	---	53.5/97	2.90	---	---	---
Weight of Particulates, mg/100ml	0.10	0.47	22.16	0.08	0.22	0.36
Repeat test	---	0.88	21.82	---	---	---
Light Absorbance,						
650 nm	0	0	0.030	0	0.001	0
Repeat	---	0	0.025	---	---	---
575 nm	0	0.001	0.119	0.002	0.005	0
Repeat	---	0.006	0.098	---	---	---
540 nm	0	0.009	0.235	0.008	0.013	0
Repeat	---	0.017	0.193	---	---	---
500 nm	0	0.027	0.497	0.015	0.024	0.030
Repeat	---	0.042	0.414	---	---	---
Adherent Insolubles, mg/100ml	0.3	0.85	60.5	0.05	0.75	1.45
Repeat test	---	2.20	4.85	---	---	---
Steam Jet Gum on						
Filtered Sample, mg/100ml	0.2	24.2	31.3	6.4	1.2	1.0
Repeat test	---	13.2	56.4	---	---	---

TABLE 15-18. COMPATIBILITY OF SHALE AND PETROLEUM DIESEL FUELS--MODIFIED 80 C OXIDATION TEST

Fuel Description Test Days	Shale DFM		Petroleum-Based DF-2		50/50 Blend	
	3	7	14	3	7	14
Color, D 1500, Before/After	0.5/0.5	0.5/1.5	0.5/3.5	1.0/1.0	1.0/1.0	1.0/1.5
Repeat test	---	0.5/1.0	0.5/3.0	---	---	---
Glass Fiber Filter Rating	3/1	14/2	20/2	8/2	10/2	10/2
Visual - Top/Control	---	17/2	20/2	---	---	---
Repeat test	---	66.0/96.0	0/99.5	775./94.0	73.5/93.2	68.9/93.2
Reflectance - Top/Control	92.5/100	---	---	---	---	---
Repeat test	---	44.5/97.5	2.5/92.0	---	---	---
Weight of Particulates, mg/100ml	0.02	2.02	43.26	0.02	0.18	0.14
Repeat test	---	2.06	25.58	---	---	---
Light Absorbance,						
650 nm	0	0.001	0.028	0.003	0.005	0.006
Repeat	---	0.002	0.034	---	---	---
575 nm	0	0.015	0.123	0.018	0.020	0.025
Repeat	---	0.013	0.111	---	---	---
540 nm	0	0.038	0.260	0.036	0.040	0.049
Repeat	---	0.030	0.209	---	---	---
500 nm	0	0.099	0.604	0.075	0.084	0.101
Repeat	---	0.078	0.472	---	---	---
Adherent Insolubles, mg/100ml	0.2	0.5	4.9	0.3	0.2	0.3
Repeat test	---	0.3	2.4	---	---	---
Steam Jet Gum on						
Filtered Sample, mg/100ml	0.6	42.8	88.2	23.8	5.2	4.2
Repeat test	---	29.6	153.2	---	---	---

### Compatibility with Metals(15-7)

The interaction of the fuels with selected metals was studied in a series of tests in which a standard metal coupon was immersed in a fuel sample for periods of up to 32 weeks at 25 C. The metals were copper, monel, mild steel, 70/30 copper/nickel, and 304 stainless steel. The metal coupons were prepared by: polishing on a buffing wheel; wiping; and rinsing first with boiling toluene and then with boiling acetone. At preselected periods of time, the coupons were removed from the fuel, cleaned of adherent fuel and deposits, then weighed to determine the weight loss during exposure. Selected fuel properties were measured to determine changes during the period of contact.

When fuels which are used by the Navy for ship propulsion are exposed to metals such as steel, seawater is often present. The effect of moisture in the compatibility test was explored with the two fuels. Synthetic seawater was added to samples of the fuels in the volumetric ratio of 1 to 9, and a metal coupon was suspended in the fuel layer with a string. Copper and mild steel specimens of 1 in x 1 in x 1/16 in. were used. The corrosion was measured as weight loss or gain per specimen and calculated in mils per year.

Immersion tests of five metals in shale JP-5 and shale DFM were completed for three or more selected time periods, including one for 32 weeks. The 70/30 copper/nickel and the 304 stainless steel coupons were immersed for all five preselected periods (2, 4, 8, 16, and 32 weeks). Weight losses were determined and were converted to inches of penetration per year (in/yr). In no instance was the penetration rate as great as 1 mil/yr (0.001 in/yr), a level considering trivial. In fact, the largest penetration found during these tests was  $3.6 \times 10^{-5}$  in/yr (70/30 copper/nickel after 16 weeks immersion). It was concluded that any attack of the neat fuels on the five metals was insignificant.

In all tests where seawater was used along with fuel, the corrosive penetration was also found to be insignificant. The shale DFM and shale JP-5, even in the presence of seawater, are not corrosive to such susceptible metals as copper and mild steel. Similar experiments were made with petroleum-based fuels with similar results.

### Compatibility with Elastomers(15-7)

The interaction of the fuels with elastomers was evaluated according to ASTM D471 by determining the effect of immersion of the selected material in the fuel at 73°F for 46 hr. The diesel fuel was exposed to four elastomers: a nitrile hose compound, a nitrile O-ring compound, a Viton fluorocarbon O-ring compound, and a urethane tank coating compound. The tensile strength and the ultimate elongation determined on the elastomer samples before and after immersion in the fuel were measured and reported as percentage increase in volume. For comparison, elastomer samples also were immersed in petroleum-derived

DFM and JP-5. The fuel samples that had been used in the immersion tests were analyzed (interfacial tension (IFT), refractive index (n), and differential infrared (IR) analysis) to determine whether or not they had changed after exposure to the elastomers.

Tests on the elastomers before and after immersion in the synfuels were completed. The data on the tensile strength, ultimate elongation, and swelling are recorded in Table 15-18.

Examination of these data lead to the following conclusions:

1. Contact with the fuels had little or no effect on the tensile strength of the two nitrile elastomers or of the urethane rubber. This assessment takes into account that variations in measured values of 10 percent or more may be encountered with replicate unexposed samples of elastomers.
2. Exposure to the shale fuels caused decreases in the magnitude of the tensile strength of the fluorocarbon elastomer similar to the decreases obtained when the elastomer was exposed to the same boiling range petroleum-based fuels.
3. Immersion in any of the fuels did not significantly affect the ultimate elongation of the two nitrile rubbers and the urethane rubber. A decreased elongation of the fluorocarbon provided further evidence of a significant change in the fluorocarbon elastomer during immersion in either the petroleum-derived or shale-derived test fuels.
4. The degree of swelling produced by immersion in both the synfuels and petroleum fuels was minor. On the average, the percentage increase in volume caused by the shale fuels was no greater than that caused by the petroleum fuels.

In summary, these data show little or no evidence of deterioration of representative nitrile and urethane elastomers in fuels derived from shale or petroleum. Small but significant changes in the properties of a fluorocarbon elastomer occurred in both types of fuels to about the same extent.

#### Effect of Elastomers in Fuel(15-7)

When the elastomer specimens were removed following exposure, the fuel remaining was retained for measurement of IFT and refractive index and for examination by IR. The results of measurements of IFT and refractive index are given in Table 15-19. Examination of these results

TABLE 15-18. EFFECT OF SHALE-DERIVED FUELS ON ELASTOMERS<sup>(15-7)</sup>

Tests	Nitrile Hose	Nitrile O-Ring	Flurocarbon O-Ring	Urethane Tank Coating
Tensile Strength, psi				
Initial (Shale DFM)	3540	2080	1800	3685
Initial (Shale JP-5)	3060	2100	1910	-
After Immersion				
In Shale DFM	3360	2060	1470	3530
In DFM	3150	2020	1280	3780
In Shale Jet	3080	2100	1385	-
In JP-5	3350	1990	1520	-
Ultimate Elongation, Percent				
Initial (Shale DFM)	375	336	165	530
Initial (Shale JP-5)	405	370	185	-
After Immersion				
In Shale DFM	370	340	140	550
In DFM	330	340	130	550
In Shale JP-5	370	310	135	-
In JP-5	395	340	160	-
Swelling, Percent Change in Volume				
Shale DFM	2.2	1.6	2.5	0.3
DFM	3.5	1.6	1.9	0.5
Shale JP-5	1.5	3gth, psi		
JP-5	2.5	2.2	1.7	-



TABLE 15-19. EFFECTS OF ELASTOMER IMMERSION ON FUEL PROPERTIES<sup>(15-7)</sup>

Elastomer	Shale DFM		Std DFM		Shale JP-5		Std JP-5	
	IFT	n*	IFT	n	IFT	n	IFT	n
Initial	41	1.4643	-	-	43	1.4492	-	-
Nitrile Hose	27.4	1.4647	26.0	1.4642	26.8	1.4492	31.4	1.4590
	27.0	1.4647	25.2	1.4642	26.9	1.4492	31.7	1.4590
Nitrile O-Ring	27.3	1.4645	23.0	1.4647	21.7	1.4492	24.6	1.4590
	29.6	1.4644	22.0	1.4648	23.4	1.4492	24.2	1.4590
Viton O-Ring	28.1	1.4647	31.1	1.4640	38.4	1.4492	37.2	1.4590
	28.5	1.4647	31.1	1.4640	38.3	1.4492	37.1	1.4590
Urethane Coating	30.6	1.4647	25.2	1.4647	-	-	-	-
	30.6	1.4645	22.7	1.4647	-	-	-	-

\*n is refractive index

on the fuel samples remaining after the elastomer immersion tests leads to the following conclusions:

1. The effect on the refractive index of the fuels was very small with changes occurring only in fourth decimal place. Consequently, the determination of the refractive index will be deleted from future test programs relating to elastomer-fuel interactions.
2. Contact with the elastomers resulted in reductions of the IFT in all cases. Because low IFT values are often associated with stable emulsions, the direction of the change is undesirable, although it is believed that the magnitude of the reductions is not yet serious. However, in future elastomer-fuel tests, the fuel remaining after the immersion period will be tested for demulsification time by ASTM D1401.

When the post-immersion fuels were examined by differential infrared (DIF) analysis for changes in the spectra, the baselines were provided by samples of the same fuels which had been stored in the refrigerator at 40°F (4°C) during the immersion test period free from contact with the elastomers. Table 15-20 shows the location and magnitude of the bands detected in the DIR spectra of the fuels after exposure to the elastomers.

Both the shale DFM and petroleum DFM showed weak absorption bands at 1720 and 1215  $\text{cm}^{-1}$ , stronger bands at 1065  $\text{cm}^{-1}$ , and the

longest bands at  $825\text{ cm}^{-1}$ . The shale JP-5 fuel showed weak absorption at  $1120$  and  $1065\text{ cm}^{-1}$  and the standard JP-5 fuel only at  $1120\text{ cm}^{-1}$ . Absorption bands in the  $1720\text{ cm}^{-1}$  region almost always indicate carbonyl groups (C=O). The bands at  $1250$ - $1000\text{ cm}^{-1}$  are indicative of C-O stretching such as are found in esters and carboxylic acids. The strongest band, which was found at  $825\text{ cm}^{-1}$ , is usually indicative of ring deformation (CH). The small indication of change in the region where carboxyl is found is a sign that very few of the spectral changes observed are due to oxidation of the fuel during the immersion tests. The appearance of bands in the petroleum DFM which were of the same magnitude and location as those in the shale DFM is further indication that no unusual deleterious effect in the shale DFM had developed.

Additional experiments were conducted in an effort to determine the cause of the peaks, especially the strong ones. Standard infrared spectrograms were made of samples of components used in the manufacture of elastomers. The spectra of these components did not relate to the differential peaks observed in the fuels used in the immersion tests.

#### Compatibility with Coatings(15-7)

The interaction of the fuels with selected tank coatings was evaluated by examining the fuel and coatings after they had been in contact for 48 weeks. Coated (4 in x 2 in x 1/8 in) steel panels were inserted into about 900 ml of fuel in closed jars which were stored at  $110\text{ F}$  ( $43.3\text{ C}$ ) for periods of up to 48 weeks. The two coatings tested were an epoxy coating and an inorganic zinc coating. After exposure to the fuel, the coatings were examined for discoloration and loosening of the coating from the underlying steel panel. The fuels were examined by IR spectroscopy, IFT determination, and refractive index for evidence of deterioration.

The effects of DFM on the two coatings were evaluated by visual observation and by the knife test. There was no discoloration or other superficial sign of coating failure. The knife test in which adhesion is checked by making knife scratches in the form of an "X" in the coating showed that the coatings were still strongly adherent.

The effects of the coatings on shale DFM are shown in Table 15-21. The IFT of the shale DFM was lowered by the contact with both coatings at  $110^{\circ}\text{F}$  ( $43^{\circ}\text{C}$ ), falling from an original  $41.5\text{ dynes/cm}$  to approximately  $28\text{ dynes/cm}$  after 48 weeks of exposure. Experience has shown that emulsion formation is seldom a problem when fuel IFT values are above  $30\text{ dynes/cm}$  and that emulsions frequently are formed when the IFT values are less than  $20\text{ dynes/cm}$ . Values of IFT between  $20$  and  $30\text{ dynes/cm}$  are in a transition range. In this instance, an IFT value of  $28\text{ dynes/cm}$  is probably acceptable and may be equivalent to that of the fuel given the same temperature exposure without contacting the

TABLE 15-20. EFFECT OF ELASTOMER IMMERSION OF INFRARED ABSORPTION OF FUELS\* (15-7)

Elastomer	1720 (cm <sup>-1</sup> )		1215 (cm <sup>-1</sup> )		1120 (cm <sup>-1</sup> )		1065 (cm <sup>-1</sup> )		825 (cm <sup>-1</sup> )	
	Shale	Petroleum	Shale	Petroleum	Shale	Petroleum	Shale	Petroleum	Shale	Petroleum
DFM										
Nitrile Hose	2 1	5 1	1 -	2 -	- -	- -	9 7	6 3	32 22	27 18
Nitrile O-Ring	trace 2	1 trace	- 1	- -	- -	- -	6 7	10 5	21 26	32 19
Viton O-Ring	2 7	5 1	trace 2	1 -	- -	- -	12 -	12 7	35 -	35 25
Urethane Coating	5 -	4 2	1 -	1 trace	- -	- -	8 4	15 5	27 16	40 17
JP-5										
Nitrile Hose	- -	- -	- -	- -	-3 -3	7 4	-6 -4	- -	- -	- -
Nitrile O-Ring	- -	- -	- -	- -	-4 -5	- -	-5 -4	- -	- -	- -
Viton O-Ring	- -	- -	- -	- -	-5 -4	- -	-5 -4	- -	- -	- -

\*Percent change in absorption at selected wave numbers; duplicate values are given.

- Means no significant change.

TABLE 15-21. EFFECT OF COATING CONTACT ON SHALE-DERIVED FUELS (Contact at 40 C)(15-7)

Coating and Contact Time	Shale DFM		Shale JP-5	
	IFT	$n$	IFT	$n$
Epoxy Coating				
0 - Days	41.5	1.4648	43.1	1.4492
12 - Weeks	38.2	1.4648	33.7	1.4486
24 - Weeks	35.6	1.4560	-	-
36 - Weeks	34.9	1.4651	34.1	1.4486
48 - Weeks	28.7	1.4650	-	-
Inorganic Zinc Coating				
0 - Days	41.5	1.4648	43.1	1.4492
12 - Weeks	41.2	1.4650	42.9	1.4490
24 - Weeks	41.0	1.4650	34.7	1.4490
36 - Weeks	39.9	1.4651	22.5	1.4610
48 - Weeks	28.2	1.4646	-	-

\* $n$  is refractive index.

coatings. Moreover, in shipboard tanks, where the ratio of coated surface to fuel volume would be much smaller, the effect on IFT would also be less. Changes in refractive index were also insignificant. At the halfway point of the exposure period the shale JP-5 results indicated no serious deterioration in IFT or refractive index.

It is concluded that any interaction between the coatings and the shale DFM has been minimal. Therefore, storage of similar shale-derived fuel in tanks coated with such materials should produce no harmful effects on fuel or coating. Tests thus far show equally good results with the shale JP-5.

#### Compatibility with Filter Equipment Components(15-7)

Interaction of the fuels with filter and filter/separator elements was evaluated by determining the effect of immersing a cross-sectional slice of the element in shale DFM for periods of up to 48 weeks. After storage for the specified time at 100 F (43.3 C), an element was examined for evidence of deterioration such as disintegration of the filter structure. The fuel was examined for changes in such characteristics as the IR spectrum, the IFT, or the refractive index of the fuel.

The container was examined weekly for evidence of filter deterioration. After immersions of 18, 24, and 36 weeks, a small amount of fuel was removed from the container and examined for fuel deterioration. A more thorough examination of the filter elements as well as the fuel was made at the end of the 48 weeks of storage.

Visual inspection was made of the filter and filter/separator elements in the shale DFM every six weeks during the 48-week immersion test. There were no visible signs of deterioration, e.g., no signs of particulates coming from the prefilter elements, and the structural integrity of the prefilters was maintained.

After the 48-week immersion test of the prefilter element was completed, the test fuel was examined also. The refractive index had increased from the initial 1.4648 to 1.4658. After the 48-week test, the IFT of the fuel had decreased from the initial 41 dynes/cm to 19.6 and 21.6 dynes/cm in duplicate samples. Part of this decrease can be attributed to the normal decrease that occurs during aging of the fuel. Also the change is accentuated by the small volume of fuel relative to the mass of the prefilter segment used in the test.

Three different filter/seperator elements were used in duplicate tests in the diesel fuel: a Fram; a Velcon, coarse; and a Velcon, fine. As in the case of the prefilter elements, there were no signs of deterioration of the elements and the refractive index of the fuel again had increased to 1.4658. The 48-week IFT values for duplicate samples were:

<u>Filter Element</u>	<u>IFT Dynes/cm</u>
Fram	23.8/21.4
Velcon, Coarse	14.8/16.3
Velcon, Fine	16.0/14.2

These values all represented a considerable drop from the initial IFT value of 41.0 dynes/cm. These IFT levels were in the range where emulsification might be abetted or stabilized. Although there is no absolute breakpoint, experience indicates that when the IFT of a fuel drops below 20 dynes/cm, filter problems often occur due to emulsion stabilization. The significant difference between the IFT of the fuel exposed to the Fram filter and that of fuel exposed to either of the Velcon filters indicated a definite effect due to the filter element in addition to the normal aging effect of the fuel. In the shipboard situation the effect on IFT would be diffused over a much larger volume of fuel.

### Lubricity

The four-ball test was used as a measure of the relative wear of moving parts by fluids of differing lubricities. The scar diameter of 0.57 mm obtained with the shale DFM was well within the range of 0.47 to 0.86 mm obtained with eight commercially available petroleum-based

diesel fuels. The shale JP-5 yielded a scar diameter of 0.69 mm, well within the same range. The results of these tests suggest that no undue lubricity problems should be expected with either of these shale-derived fuels.

#### Hydroperoxide Formation in Jet Fuels(15-14)

Hydroperoxides in jet fuel have been recognized as the cause of degradation of aircraft fuel system elastomers (see previous discussion on compatibility of shale-derived fuels with elastomers). Laboratory studies indicate that a fuel with a peroxide number (determined by ASTM method D3703-78 with the exception that Freon 113 replaced carbon tetrachloride as the solvent) greater than 1 can be detrimental.

Examination of fuels refined by different processes have demonstrated that significantly higher peroxide numbers were obtained with fuels that had been severely hydrotreated, although interlaboratory agreement of the precise numbers has been poor.

Hindered, phenols, particularly those with t-butyl groups in both positions ortho to the phenol group, provided the best protection against peroxidation at a concentration of 24 parts per million. Data for shale JP-5 are illustrated in Figure 15-1. The three data sets agree fairly well in overall pattern and are consistent in the first few days of testing in an accelerated test conducted at 100 C. This fuel, although containing a hundred phenol antioxidant, attained high levels of peroxidation and exceeded a peroxide number of 1 in two days. The peroxide number dropped sharply after the fifth day in storage and stabilized at an acceptable level.

#### Microbial Deterioration of DFM(15-15)

Problems from microbial fuel contamination generally arise from two distinctly different groups of microorganisms, sulfate-reducing bacteria and fungi. In an oxygen depleted two-phase fuel/water system, the bacteria thrive by the reduction of sulfate to sulfides, which accelerates corrosion in storage tanks and fuel handling systems and generates particulate matter. The fungi, on the other hand, require oxygen, and the most troublesome species tend to form coherent mats at water/fuel interfaces which can clog filters and orifices.

Growth responses of various microorganisms to jet fuels from oil shale and coal have been studied and shown to be markedly different. A Fusarium fungus grew as well in all synthetic fuels as in petroleum JP-5. Sulfate-reducing bacteria were relatively inhibited only in a shale fuel containing considerable concentrations of basic nitrogen compounds. This fuel was also inhibitory to the fungus, Cladosporium resinae, and a yeast (Candida sp.) but no inhibition was noted with another shale oil fuel from which the nitrogen constituents were almost

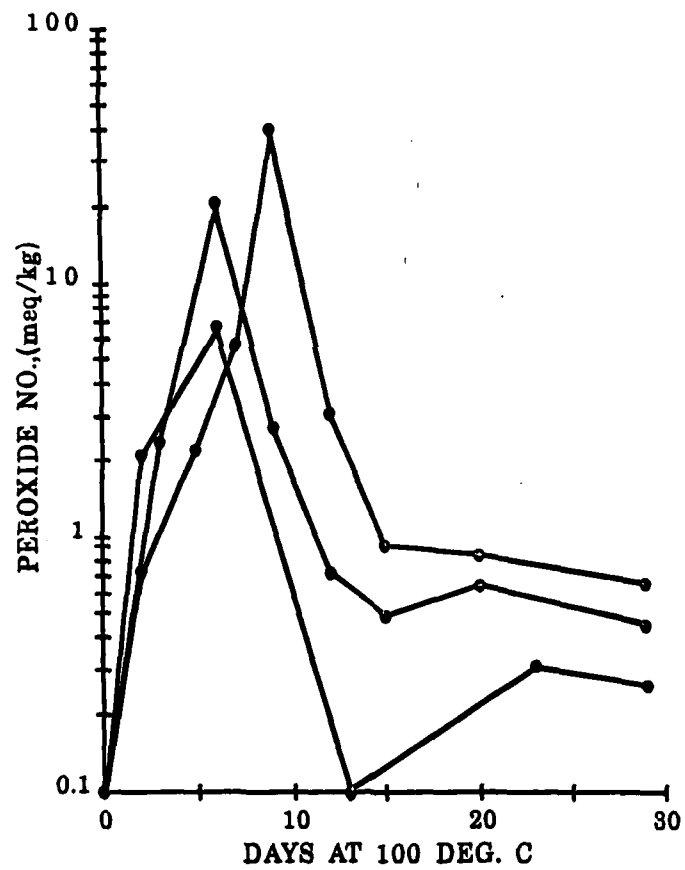


FIGURE 15-1. PEROXIDATION OF SHALE II  
JP-5 SAMPLE IN TRIPLICATE

completely removed by hydrogenation and acid extraction. The coal-derived fuels examined were highly inhibitory to fungi. Apparently microbial growth varies with the species of organism, the source of the fuel and the refining processes used.

In no case was the growth of a microbial fuel contaminant promoted significantly by the presence of a diesel fuel from oil shale as compared with conventional petroleum-derived diesel fuel. Certain of the important fungal contaminants were initially inhibited somewhat by the synthetic diesel fuel which indicated that a period of adaptation was necessary before the growth rate become comparable to that observed in the presence of petroleum fuel. Thus, the use of a synthetic diesel fuel derived from shale oil, either alone or in mixtures with conventional fuel, is not likely to lead to microbial contamination problems significantly different from those encountered in the past.

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## 16. TOXICOLOGY OF SHALE OIL AND SHALE PRODUCTS

Introduction

The toxicology of shale oil, unfinished shale fuels, and finished shale fuels has been investigated in detail by two organizations: the DOE Oak Ridge National Laboratory and the Naval Medical Research Institute, Toxicology Detachment.

In the Oak Ridge program, 11 types of shale derivatives were used as material for study, and 16 types of tests were carried out by 19 investigators. These studies have resulted in a number of publications, which are referenced at the end of this section. Several of the studies have not yet been completed. Representative data from those that are finished are summarized herein to substantiate the conclusions reached to date.

The Navy studies were focused primarily on evaluating long-term effects due to chronic exposure to shale- and petroleum-derived DFM and JP-5. Small mammals were exposed via inhalation, skin and eye inoculation, and direct injection. While many of these studies are also still in progress, the results to date are sufficient to draw strong preliminary conclusions about the health effects of shale distillates.

The Oak Ridge Shale Oil Toxicity ProgramObjective

The objective of this large and multi-faceted study was to evaluate the potential health effects arising from the use of shale oil derivatives as fuels.

Procedure

Crude shale oil and numerous derivatives were subjected to a broad spectrum of chemical and biological tests to assess a variety of health effects. Testing was often performed in such a way that direct comparisons could be made between fuels derived from shale oil, coal, and petroleum.

Tables 16-1 and 16-2 show the scope of activities undertaken in support of this effort. Table 16-1 lists the various tests performed on the fuels of interest while Table 16-2 identifies the principal investigators and their affiliations. Several of the studies cited in Table 16-1 are summarized herein, as well as others performed elsewhere.

Scientists at Oak Ridge National Laboratory were responsible for storing reserves and distributing samples of shale derivatives and other fuels as operators of the EPA/DOE Fossil Fuels Research Materials Facility. (16-17,20) Reserves were stored in darkness at 4 C and were distributed upon request in such a way that samples were uniform and free of contamination. Stability monitoring and physical and chemical characterization were also performed at this facility.

Tests performed upon crude shale oil and its derivatives are grouped into four categories herein for ease of discussion:

- o Sample fractionation and quantitative analysis to determine the presence of known carcinogens; (16-5,7,8,9,14,21)
- o Identification of mutagenic activity via bioassay of standardized bacterial species; (16-6,12,16,28,29)
- o Evaluation of toxicity, teratogenicity and other deleterious effects upon microbes and simple aquatic species; (16-10,11,16,30,31) and
- o Investigations with small mammals to assess carcinogenicity, toxicity, ocular and dermal irritability and dysfunction of major organs. (16-6,15,16,23,27,29)

## Results

The magnitude of the effort undertaken to investigate shale fuels health effects precludes a case-by-case discussion of the results achieved. Fortunately, the trends observed across the full spectrum of research activities were largely uniform and lead to entirely plausible conclusions. Initially, therefore, a broad summary of the results will be presented and discussed. This summary will then be substantiated with representative data selected from the four categories previously described.

Table 16-3 is a verbatim reproduction of an executive summary prepared by Oak Ridge National Laboratory describing their oil shale health effects research. (16-6) The summary is based on Oak Ridge's deep involvement in all phases of the program. The observations presented in Table 16-3 and reinforced in independent investigations conducted elsewhere can be briefly paraphrased as follows:

- o Within a given fuel type, shale-derived liquids usually exhibit more detrimental health effects than petroleum fuels but are significantly less hazardous than coal-derived liquids.

- o The species most responsible for detrimental health effects are polynuclear aromatic compounds (PNAs), particularly those bearing nitrogen- or oxygen-containing radicals.
- o Hydrotreating and other refining steps that reduce the incidence of such PNAs correspondingly reduce the associated health risks.
- o Highly refined shale-derived fuels such as JP-5 and DFM are virtually identical to their petroleum-based counterparts in terms of health effects.

Because many PNAs have been demonstrated to be potent carcinogens, several investigations were conducted to quantify the amounts of selected species present in shale, coal and petroleum liquids. (16-7,8,9,21)

Table 16-4 includes data abstracted from Tomkins, et al., (16-7) who determined the amount of benzo(a)pyrene (BaP) present in several crudes and derivatives. Generally speaking, the coal liquids tested have substantially more BaP than the shale liquids, which in turn have higher concentrations than the petroleum crudes. Note also the relatively miniscule BaP concentration in the highly refined shale DFM. In view of BaP's role as a carcinogen, one would expect the carcinogenic potential of the fuels to be highest for coal liquids and lowest for petroleum with shale intermediate.

Figure 16-1 presents data on mutation frequencies that support this expectation. (16-6) Four coal liquids, three shale oils and a petroleum crude were evaluated for mutagenicity. Each fuel specimen was tested twice in duplicate at the designated concentration. The shale residues were more mutagenic than the petroleum crude but far less so than the coal liquids. These trends are in agreement with mutagenicity data reported elsewhere. (16-12,16.28)

The toxicity of coal, shale and petroleum liquids to fresh-water algae was determined by measuring the photosynthetic output of colonies subjected to varying concentrations. (16-11)

Tables 16-5 and 16-6 consist of descriptions of the materials tested and the responses of two algal species to those materials, respectively. The shale materials tested are Paraho crude and derivatives. The results follow the trends described previously: coal liquids caused substantial reductions in photosynthetic output, indicating a high degree of toxicity. Algal species subjected to petroleum derivatives were significantly affected only at 100 percent water-soluble fraction (WSF, prepared by mixing oil and water in a 1:8 ratio, stirring for 16 hours and discarding the insoluble fraction). Shale liquid toxicities fell between those of coal and petroleum liquids. The abundance of phenols, amines and other polar aromatics in coal liquids was expected to have increased their solubility in water, thereby

exposing the algae to greater concentrations of toxic substances (see column A<sub>254</sub> values, Table 16-5).

Numerous experiments evaluating carcinogenicity, toxicity and organic dysfunction in small mammals exposed to various grades of coal, shale and petroleum liquids have been performed. (16-6,15,16,23-27,29) A comparative study of the acute toxicities of crude and refined shale and petroleum liquids was completed by Oak Ridge National Laboratory. (16-27) Acute toxicity was evaluated on the basis of five tests:

- (1) Acute lethality in mice following oral and intra-peritoneal administration
- (2) Acute dermal toxicity in rats
- (3) Delayed allergic contact hypersensitivity in guinea pigs
- (4) Primary eye irritation in rabbits
- (5) Primary skin irritation in rabbits.

The results indicate that crude shale oil and its derivatives exhibit essentially the same low toxicities as their petroleum counterparts. Fuels from both sources were nonirritating to the skin and eye. The researchers conclude that "acute toxicity of Paraho Crude Shale Oil and of five derivatives does not appear to be a problem of immediate concern". (16-27)

Chronic dermal toxicity was also evaluated at Oak Ridge National Laboratory. (16-16) Mice were subjected to dermal application of shale and petroleum crude oil and derivatives for periods ranging from 40 to 60 weeks. The mice were evaluated for evidence of skin tumor induction and systems toxicity.

Crude and hydrotreated shale oil and the hydrotreated residue were found to be carcinogenic in mouse skin. Distillates derived from shale oil and petroleum were also carcinogenic, although far less so than the crude and hydrotreated specimens. The shale distillates were slightly more active than their petroleum counterparts. At the time of writing, however, the statistical significance of this finding had not been substantiated.

Kidney injury was observed following chronic dermal exposure to both shale and petroleum middle distillates. Further studies are under way to determine the implications of this finding for human health.

### Naval Medical Research Institute Studies

The Naval Medical Research Institute/Toxicology Detachment (NMRI/TD) at Wright-Patterson Air Force Base was responsible for a broad series of tests comparing shale- and petroleum-derived JP-5 and DFM. (16-1,2,3,4,34,35,36,37) These and other refined products are particularly important because human exposure to them is likely to be substantially higher than to crude or intermediate species.

Many of the tests conducted at NMRI/TD were designed to evaluate long-term effects due to chronic exposure to shale and petroleum distillates. The protocol often calls for necropsy following a period approximating the test animal's normal lifetime. Accordingly, many experiments are still in progress and are scheduled for completion in October 1984. Test subjects have been small mammals including mice, rats, guinea pigs, rabbits and dogs. Eye and skin irritation were evaluated in addition to long-term effects such as altered body weight and damage to specific organs.

With minor differences, the results to date indicate that the health effects due to chronic exposure to shale JP-5 and DFM should be essentially indistinguishable from those attributable to petroleum JP-5 and DFM. These findings corroborate those recorded at Oak Ridge National Laboratory and reinforce the view that satisfactorily refined shale fuels can be substituted for their petroleum-derived equivalents without adverse effects.

### Conclusions

The health effects of crude shale oil and its derivatives were investigated in a broad range of experiments. The presence of known carcinogens was measured via chemical fractionation and quantitative analysis. Mutagenicity was determined through bioassay of standardized bacterial species. Toxicity, carcinogenicity and organic dysfunction were investigated in tests with microbial species, simple aquatic animals and small mammals.

Highly refined shale derivatives such as JP-5 and DFM exhibited health effects similar to their petroleum-derived counterparts. Crude shale oil was found to be more harmful than petroleum crude, due largely to greater concentrations of oxygen- and nitrogen-bearing polynuclear aromatics (PNAs). Coal liquids, which contain significantly more PNAs than shale liquids, were found to exhibit correspondingly higher levels of toxicity and carcinogenicity. The results of these studies indicate that the use of highly refined shale derivatives low in oxygen and nitrogen content should not present significant health hazards beyond those exhibited by their petroleum-derived counterparts.

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- 16-37. Gaworski, C. L., MacEwen, J. D., Vernot, E. H., Bruner, R. H., and Cowan, M. J., Jr., "Comparison of the Subchronic Inhalation Toxicity of Petroleum and Oil Shale JP-5 Jet Fuels", Naval Medical Research Institute/Toxicology Detachment, Wright Patterson Air Force Base, Ohio (undated).

TABLE 16-1. OAK RIDGE TOXICOLOGY STUDY MATRIX OF THE PARAHO/  
SOHIO CRUDE AND REFINED SHALE OIL SUITE(a) (16-20)

Repository Number	Research Material	Test	Chemistry							Biology, Ecology									
			Comprehensive Analysis	PAH Analysis	Stability Screening	Special Studies	Chemical Class Fractionation	Mouse Skin Carcinogenesis	Bacterial Mutagenesis	Drosophila Mutagenesis	Acute Oral Toxicity to Mice	Pond Ecosystem Effects	Marine Ecosystem Effects	Combustion Products Mutagenicity	Cilia Toxicity	Mouse Lung Tumorigenicity, Skin & Eye Irritation, Toxicity	Mice Interperitoneal Tumorigenesis	Trout Embryo Larvae Hatching & Morphology	
4601	Crude Shale Oil	1	2,5	15	15	16	3-5	5-7	8,9	10	11	—	—	13	17	18	19		
4602	HDT Shale Oil	1	2,5	15	15	16	3-5	5-7	8	10	11	—	—	13	17	18	—		
4603	Weathered Gas Feedstock	1	—	15	—	16	—	6	8	—	—	—	—	—	—	—	—		
4604	JP-5 Precursor	1	—	15	—	16	—	6	8	—	—	—	—	—	—	—	—		
4605	JP-8 Precursor	1	—	15	—	16	—	6	8	—	—	—	—	—	—	—	—		
4606	DFM Precursor	1	2	15	—	16	3,4	6	8	—	—	—	—	—	—	—	—		
4607	HDT Residue	1	2,5	15	15	16	3-5	5,6	8	10	11	—	—	13	17	—	—		
4608	JP-5 Product	1	5	15	—	16	3-5	5,6	8,9	—	11	—	—	—	17	—	—		
4609	JP-8 Product	1	5	15	—	16	3-5	5,6	8	—	—	—	—	—	17	—	—		
4610	DFM Product	1	2,5	15	15	16	3-5	5,6	8	—	11	14	12	13	17	18	—		
4612	Acid Sludge	1	—	—	—	16	—	6	8	—	—	—	—	—	—	—	—		
4614	Petroleum JP-5	—	5	15	—	16	4,5	5,6	8,9	—	11	—	—	—	17	—	—		
4615	Petroleum JP-8	—	5	15	—	16	4,5	5,6	8	—	—	—	—	—	17	—	—		
4616	Petroleum DFM	—	5	15	—	16	3	5,6	8	—	11	14	—	13	17	18	—		

(a) Numbers in Table 16-1 are identification numbers for investigators listed in Table 16-2.

TABLE 16-2. INVESTIGATORS, OAK RIDGE TOXICOLOGY STUDIES (16-20) (a)

Number	Investigator	Institution/Company
1	L. W. Burdett	Union Oil Company <sup>b</sup>
2	S. C. Blum	Exxon Corporation <sup>b</sup>
3	W. Barkley	Kettering Laboratory <sup>b</sup>
4	J. M. Holland	Oak Ridge National Laboratory
5	L. M. Holland	Los Alamos Scientific Laboratory
6	J. L. Epler	Oak Ridge National Laboratory
7	F. T. Hatch	Lawrence Livermore Laboratory
8	S. Zimmering	Brown University
9	M. Legator	University of Texas
10	H. P. Witschi	Oak Ridge National Laboratory
11	J. M. Giddings	Oak Ridge National Laboratory
12	D. L. Coffin	U. S. Environmental Protection Agency
13	J. N. Dumont	Oak Ridge National Laboratory
14	N. Richards	U. S. Environmental Protection Agency
15	W. H. Griest	Oak Ridge National Laboratory
16	B. R. Clark	Oak Ridge National Laboratory
17	L. Smith	Oak Ridge National Laboratory
18	W. Pepelco	U. S. Environmental Protection Agency
19	W. Birge	University of Kentucky

<sup>a</sup>See Table 16-1.<sup>b</sup>Sponsored by the American Petroleum Institute

TABLE 16-3. SUMMARY OF RESULTS OF OIL SHALE HEALTH EFFECTS RESEARCH AT OAK RIDGE NATIONAL LABORATORY(16-16)

- 
- Paraho/Sohio Shale Oil was found to be mutagenic in the Ames assay and confirmed in the yeast system.
  - After chemical fractionation of the crude shale oil, it was found that the mutagenic activity was contributed by the organic constituents of the basic and neutral fractions.
  - Hydrotreatment of the shale oil abolished the detectable mutagenic activity and also reduced the cytotoxicity as measured in cellular systems.
  - Refined shale oil, jet fuel, and diesel fuel marine samples were not mutagenic.
  - The samples rank for their mutagenic activity as coals oils > shale oil > natural petroleum crudes and only qualitatively agree with carcinogenic activity.
  - Acute toxicity of Paraho Crude Shale Oil and its upgraded derivatives does not appear to be a problem of immediate concern.
  - The data obtained in the lung adenoma bioassay suggest that Crude Shale Oil has tumorigenic potential.
  - Paraho shale oil is carcinogenic in mouse skin.
  - Hydrotreatment reduces but does not eliminate skin carcinogenicity and appreciable carcinogenic activity remains in the residue material.
  - Kidney injury was noted following chronic dermal exposure to shale and petroleum derived middle distillates.
-

TABLE 16-4. AVERAGE BaP CONCENTRATIONS IN VARIOUS  
PETROLEUM, SHALE AND COAL PRODUCTS  
AS MEASURED BY TOMKINS ET AL(16-7)

Repository Sample No.(a)	Sample Description	Average BaP Concentration, g/g
<u>Petroleum-Derived Materials</u>		
CRM-3	Petroleum crude A	2.7
	NBS Wilmington petroleum Crude A	1.2
<u>Shale-Derived Materials</u>		
CRM-2	Crude shale oil A	11
	SRM 1580 (certified shale oil)	31.5
4601	Crude Paraho shale oil	8
4602	Hydrotreated Paraho shale oil	9
4607	Hydrotreated Paraho residue	16
4610	Paraho/Sohio DFM	0.02
<u>Coal-Derived Materials</u>		
CRM-1	Coal oil A	151
	NBS coal liquid oil (SRC-II)	179
1308	Atmospheric still overhead	0.3
1309	Atmospheric still bottom	115
1310	Vacuum still overhead	451
1311	Vacuum still bottom	233
1312	Atmospheric still overhead	5
1313	Atmospheric still bottom	37
1314	Vacuum separator overhead	260
1315	Vacuum still bottom	142
	Coal gasifier tar	61

(a) CRM: Comparative Research Material. Four-digit numbers refer to materials retained in EPA/DOE Fossil Fuel Research Materials Facility.

TABLE 16-5. OILS TESTED FOR ACUTE TOXICITY TO FRESHWATER ALGAE<sup>(16-11)</sup>

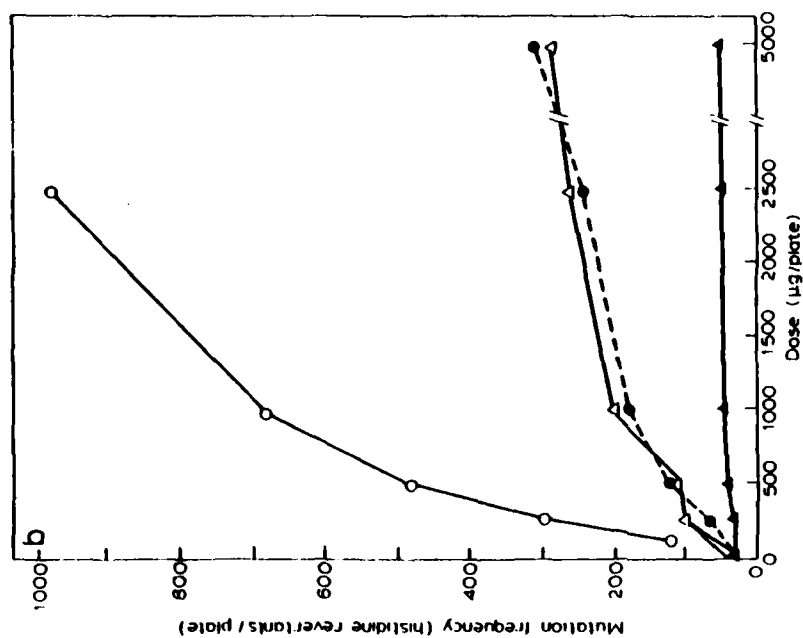
sample	EPA/OOE no.	A <sub>254</sub> <sup>a</sup>	description
CL-1	1701	25.6	fuel oil blend, noncatalytic coal liquefaction
CL-2	1601	8.8	raw distillate, catalytic coal liquefaction
CL-3	1602	12.0	same as CL-2, low-severity hydrotreatment
CL-4	1603	9.2	same as CL-2, medium-severity hydrotreatment
CL-5	1604	2.8	same as CL-2, high-severity hydrotreatment
CL-6	1308	20.4	atmospheric still overhead, catalytic coal liquefaction
CL-7	1309	2.9	atmospheric still bottoms, catalytic coal liquefaction
CL-8	1310	2.4	vacuum still overhead, catalytic coal liquefaction
CL-9	1312	21.6	atmospheric still overhead, catalytic coal liquefaction
CL-10	1313	5.9	atmospheric still bottoms, catalytic coal liquefaction
CL-11	1314	1.2	vacuum still overhead, catalytic coal liquefaction
SH-1	4601	2.8	crude shale oil, above-ground retorting
SH-2	4602	0.50	hydrotreated shale oil
SH-3	4607	0.16	hydrotreated shale oil, residue
SH-4	4608	0.007	shale oil JP-5 product
SH-5	4610	0.044	shale oil DFM product
P-1	4616	0.24	petroleum DFM
P-2	b	0.088	petroleum No. 2 diesel fuel
P-3	4614	0.060	petroleum JP-5
P-4	5401	0.096	petroleum No. 6 fuel oil
P-5	5402	0.018	petroleum No. 6 fuel oil
P-6	6101	ND <sup>c</sup>	petroleum No. 6 fuel oil

<sup>a</sup> Absorbance of water soluble fraction at 254 nm measured with a Perkin-Elmer spectrophotometer. Water-soluble fractions were diluted as necessary to read A<sub>254</sub> below 1.0. <sup>b</sup> Diesel fuel purchased from local distributor. <sup>c</sup> ND = not determined.

TABLE 16-6. RESPONSE OF SELENASTRUM CAPRICORNUTUM AND MICROCYSTIS AERUGINOSA TO WATER-SOLUBLE FRACTIONS OF COAL-LIQUEFACTION, SHALE-OIL, AND PETROLEUM PRODUCTS<sup>(16-11)</sup>

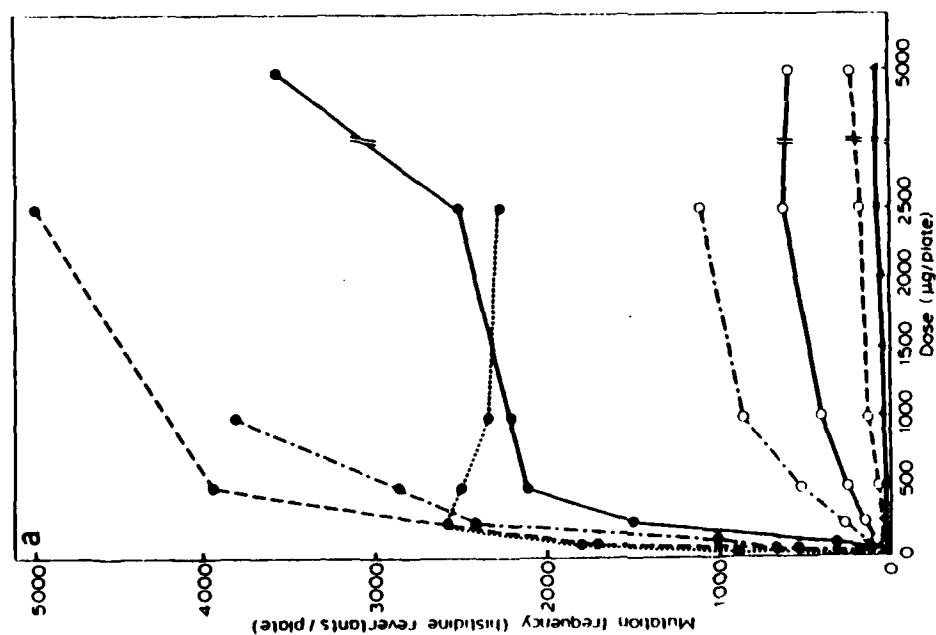
sample	WSF concn	<i>S. capricornutum</i>				<i>M. aeruginosa</i>			
		0.1%	1%	10%	100%	0.1%	1%	10%	100%
CL-1		102	73*	11*	1*	99	82*	1*	0*
CL-2		—	60*	3*	2*	—	76*	2*	1*
CL-3		—	66*	7*	2*	—	71*	2*	1*
CL-4		—	71*	5*	3*	—	94	2*	1*
CL-5		—	68*	15*	4*	—	103	4*	1*
CL-6		90*	64*	0*	—	93	74*	1*	—
CL-7		114	47*	3*	2*	99	56*	1*	1*
CL-8		73*	47*	4*	1*	85	43*	2*	1*
CL-9		61*	27*	3*	1*	114	94	3*	—
CL-10		99	35*	2*	—	91	29*	2*	1*
CL-11		65*	34*	3*	1*	85	46*	4*	2*
SH-1		—	94	21*	1*	—	70*	10*	1*
SH-2		—	113	82*	2*	—	84	67*	1*
SH-3		108	82*	24*	13*	94	101	84*	26*
SH-4		103	110	101	99	—	—	—	—
SH-5		—	93	106	84*	—	—	—	—
P-1		—	99	90	1*	—	—	—	—
P-2		95	97	91	39*	97	100	98	50*
P-3		99	108	109	90	—	—	—	—
P-4		96	112	106	90*	87	92	88	41*
P-5		87	101	98	124	100	110	103	83*
P-6		111	98	97	93	114	105	103	75*

\* The values shown are photosynthesis expressed as a percentage of controls. Asterisks indicate significant photosynthetic inhibition ( $P = 0.05$ ). Dashes indicate tests not performed.



### B. Response to crude oils

- ▲ South Louisiana Petroleum
- Paraho shale oil
- ▲ Geokinetic shale oil
- Occidental shale oil



### A. Response to residual products

- ▲ South Louisiana Petroleum
- Paraho shale oil
- Occidental shale oil
- Geokinetic shale oil
- H-Coal syncrude mode vacuum still bottoms
- Exxon Donor Solvent system residue

FIGURE 16-1. MUTATION FREQUENCY OF SALMONELLA TYPHIMURIUM STRAIN TA 98 (16-6)



## 17. CONCLUSIONS

The overall conclusions from evaluation of fuels produced by Sohio from Paraho shale crude, under the Joint DOD/DOE Shale Oil Project, are that (1) the shale DFM and the shale JP-5 are fully acceptable as fuels for Navy shipboard gas turbines, diesel engines, and boilers and (2) the shale JP-5 is fully acceptable as a fuel for Navy aircraft gas turbines.

Shale DFM proved fully satisfactory in performance and endurance tests of high-speed and medium-speed diesel engines, the DDA 501-K17 gas turbine used for shipboard generator drive, and the GE LM2500 gas turbine used as a main propulsion engine. Performance and operation of Navy boilers and burners also proved satisfactory with shale DFM. In a demonstration cruise of the USS Scott, DDG-995, shale DFM was burned in two LM2500 propulsion turbines and a DDA 501-K17 generator-drive turbine; performance was not measurably different from that with petroleum DFM.

Shale JP-5 proved to be fully satisfactory as a fuel for Navy aircraft gas turbines after treatment with additives to improve copper-strip corrosion and lubricity. In rig tests of a TF-30 combustor, combustion efficiency, stability limits, emissions, combustor liner temperatures, and combustor exit temperature profile were the same for JP-5 and shale JP-5. In full-scale tests of the T63, T56, TF30, and TF34 engines, shale JP-5 had somewhat better lightoff and altitude relight characteristics than JP-5, but other characteristics were the same. The hot sections of the T56 and TF34 engines were in excellent condition after extensive cyclic testing with shale JP-5. It was concluded that the shale JP-5 was a fully satisfactory fuel for Navy aircraft turbine engines.

Storage stability of the shale DFM and shale JP-5 proved to be excellent, and thermal stability of the shale JP-5 before and after two years of storage was well within specifications. The shale fuels were also compatible with petroleum fuels. Static and dynamic immersion tests showed that the shale fuels were compatible with elastomeric and metallic materials used in shipboard and aircraft fuel tanks, piping, hoses and seals.

Toxic and mutagenic properties of the shale DFM and shale JP-5 were investigated extensively and found to be nearly identical to those of their petroleum counterparts.

The overall conclusion from all of the evaluations carried out is that shale JP-5 and shale DFM of the quality evaluated would be satisfactory fuels for Navy ships and aircraft.

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